

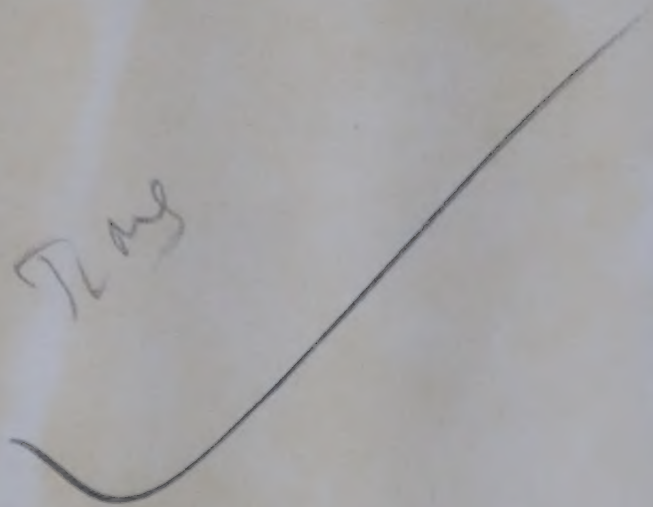
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Chemical engineering

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CHEMICAL ENGINEERING TECHNIQUES

by

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PREFACE

It has been our observation that many chemical engineering students spend a large share of their college careers without ever being fully aware that there is a systematic arrangement of the methods of chemical engineering. The fact that chemical engineering practice is the application of a number of rather well defined, interrelated, and easily classified techniques is not often brought definitely to their attention. These techniques are the tools of the profession. We feel, therefore, that students should be taught to consider them as exactly that, and should be made aware of the limitations of the methods as well as the positive features of each.

The textbook field is replete with excellent books relating to unit operations, and we have but one objection to the unit operation concept and its use in instructing chemical engineering students. This one exception is that the student is likely to be led to look upon an operation, such as distillation, or drying, or screening, as an end in itself rather than as merely a means to an end. Unfortunately some of the textbooks on this highly important subject make such a definite break between the various unit operations that they enhance rather than dispel this erroneous conception. Even those which generously sprinkle the mathematics of unit operations with material describing the equipment for conducting them often fail to point out that there are usually many equally suitable methods of reaching the same objective.

It is our purpose, therefore, in writing this text to point out the basic objectives of chemical engineering, and to present some of the more important techniques now available for reaching them. We have grouped these techniques on a functional basis with respect to their objectives, rather than classifying them as they may be related in their procedures, and have arranged the groups in such a way that a definite continuity of presentation is followed

through the book. This, we feel, will permit the student to look critically at the operations and processes of industrial practice. By this study, an attitude which may be termed analytical in its approach should be developed. We feel that any student, or any engineer, who can define an objective and who can marshal the means for reaching it, will be much advanced over the individual of equal fundamental knowledge who lacks the ability to analyze a situation properly. In other words, we believe that a correct qualitative solution to any problem of design or operation is frequently as important as the quantitative solution which follows it.

It must be stressed at this point that this text does not, in general, present numerical data relating to capacities or costs, nor does it deal with minute intricacies of equipment design or operation. It is felt that these subjects are adequately covered in the several books and handbooks now available on design and operation of chemical equipment.

We must certainly express our most sincere appreciation for the fine cooperation of the many individuals, most of them complete strangers to us, who spent much time and effort to obtain, reproduce, and send us the many pictures we have used for illustrating this text. To name all these men would be to list advertising and sales executives of nearly all the more important machinery manufacturing organizations. We are grateful to each of them for the fine assistance which they gave us, and in this most inadequate way, we say "thank you".

To Francis M. Turner, Vice President of the Reinhold Publishing Corporation, we are more than grateful for the assistance and for the persistent but kindly prodding which kept us progressing steadily in the assembly of material for this book.

We hope that "Chemical Engineering Techniques" will be well enough received to deserve a second edition, which will give us an opportunity to include all the suggestions which we feel we shall receive as a result of the somewhat unorthodox arrangement of subject material presented in this book.

January, 1952

B. E. LAUER
RUSSELL F. HECKMAN

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INTRODUCTION

Objectives of Chemical Engineering

There have been many misconceptions of the responsibility of chemical engineers in industry. The chemical engineer is a person who can visualize an objective—usually a quite simple one; determine accurately what general direction must be taken to reach this objective; conduct a rational search for methods for best performing the several steps required in reaching it; and if necessary, operate or direct the operation of equipment used for carrying out the required procedures.

The objectives of chemical engineering practice are normally straightforward, simple, and readily determined. The primary professional objective of the chemical engineer is to alter the nature of some raw material so that it becomes more useful than in its previous state, and to do this at a minimum cost. Chemical properties are those most frequently involved, although the alteration may be concerned with physical properties, such as the separation of a product from its impurities or the blending of several materials into a uniform mixture.

The chemical engineer may not always succeed in producing a commodity economically. Under certain conditions he may be compelled to reject a program; such a step may require considerable fortitude. Even after the chemist in the laboratory has developed many of the details relating to the conduct of a chemical reaction and it is turned over to the engineering staff for the design of a plant which will make it commercially feasible, the project may be turned back to the laboratory if it presents problems of industrial operation which are incapable of solution by the means available, or if the price obtainable for the product will not justify its development. Many laboratory processes have met such a fate. It is an intelligent and often a courageous

engineering staff which can decide to abandon an impractical program before extensive sums of money are spent on the purchase, installation, and operation of equipment.

Another major objective of chemical engineering is the location and elimination of aberrations in a process. For this the chemical engineer will normally find it necessary to develop and apply the diagnostic point of view to virtually all his problems.

In achieving these several general objectives, the chemical engineer should give consideration to the environment in which he, his colleagues, and plant personnel carry out their duties. The additional cost of providing clean, light, airy, and properly maintained plants is usually more than repaid in the satisfaction of workers and in increased production and profits.

To return to a generalized situation, which may be represented by a chemical equation such as



the fundamental objective of the chemical engineer becomes that of economically producing X and Y , in the state of purity and quantity required for commercial use, from raw materials A and B , which are less valuable in their initial state.

Chemical Engineering Unit Tasks

To reach this objective, it is required that a series of tasks be completed. In keeping with the generally accepted practice by authors in the chemical engineering field to refer to "unit operations" or "unit processes," these may be called "unit tasks". Referring to the generalized chemical equation above, it can be seen readily that the unit tasks are reasonably few in number. They are simply:

1. Assembly of raw materials
2. Preparation of raw materials for reaction
3. Utilization of energy
4. Control of conditions affecting the reaction
5. Separation of the products
6. Preparation of the products for shipment, for further use, for sale, or for storage.

Obviously, several of these can be broken into sub-classifica-

tions or, for uniformity, "unit sub-tasks". For example, under (1) are included:

- a. Interplant transportation
- b. Intraplant transportation
- c. Storage

The other tasks can be similarly divided. The unit tasks become the subjects of the major sections of the text, and the divisions, or sub-tasks are, in general, the subjects of its several chapters.

Chemical Engineering Techniques

After it has been determined what unit tasks and sub-tasks will be required, the final step in the process is to select the technique whereby the particular unit task or sub-task may be accomplished most effectively. It is often possible to use one of several different techniques for performing some task, but rarely are the several of equal suitability. Sometimes only one technique is satisfactory and often, when only one is available, it may be complicated, costly, and time-consuming. Sometimes no known method is available for resolving a specific task, and it is here that the ingenuity of the chemical engineer becomes most valuable. The money and labor spent in the separation of U_{235} from U_{238} and several other steps in the preparation of the products of atomic fission have certainly set a new high in research effort. It is interesting to observe in connection with this problem that it has been reported that the research program leading to this separation developed several distinctly different techniques which achieved the desired end results.

It is in the selection of the proper existing techniques that engineering experience becomes most useful. There is a premium on ingenuity in the development of new techniques or in the improvement of old ones.

Check List

Material inspectors are usually provided with a detailed check list applicable to the particular item which is being inspected. Only after every point on the list has been checked by the inspector and has been found to meet the specifications can that particular item be considered acceptable for purchase and use.

In much the same manner a list can be prepared for use in checking the selection of a chemical engineering technique. Obviously, the technique which most nearly meets all the specifications should be selected. Many or perhaps all of the following points must be considered in such a selection.

1. Physical properties of the materials
 - a. State of material, i.e., solid, liquid, gas
 - b. Vapor pressure
 - c. Freezing point
 - d. Density
 - e. Viscosity
 - f. Surface tension
 - g. Adsorptive properties
 - h. Hardness
 - i. Solubility
 - j. Size
 - k. Heat capacity
 - l. Fragility
 - m. Elasticity
 - n. Thermal resistance
 - o. Porosity
2. Chemical properties of the materials
 - a. Those involved in the principal reactions
 - b. Reactions (if any) involving metals or other materials of construction
 - c. Flammability and explosiveness
 - d. Resistance to moisture
 - e. Resistance to atmospheric exposure
 - f. Chemical stability
3. Quasi-chemical properties of the materials
 - a. Toxicity
 - b. Biological properties
4. Economic situation
 - a. Cost of plant and equipment
 - aa. Initial cost
 - bb. Depreciation, taxes, and interest
 - cc. Freight
 - dd. Installation
 - ee. Operation

- ff. Maintenance
- gg. Adaptability
- hh. Length of time to be used
- b. Quantity of material to be handled
 - aa. Quantity per unit of time
 - bb. Total quantity
- c. Labor situation
 - aa. Cost of labor
 - bb. Availability of labor
 - cc. Temper of labor unions
 - dd. State and Federal labor laws
- d. Value of material being handled
 - aa. Actual value
 - bb. Market fluctuations
- 5. Miscellaneous factors
 - a. Weather conditions
 - b. The required purity of product, i.e. sales requirements
 - c. Availability of raw materials
 - d. Production demands
 - e. General business conditions
 - f. Political situation
 - g. Power requirements and supply
 - h. Location of plant
 - i. Availability of equipment
 - j. Safety hazards
 - k. Comfort and convenience of employees

Equipment

Ordinarily several types of styles of equipment are supplied by different manufacturers, any or all of which may be suitable for use in some particular technique. A check list similar to that for the selection of the technique may be useful in the selection of the actual item of equipment. Frequently the specification of equipment will be made upon the recommendation of a reputable manufacturer, and the purchase made on a cost and guaranteed performance basis after the general type of equipment required for the operation has been determined.

Various agricultural, construction, and general industrial equipment, and even domestic appliances, are often quite satisfactory

for performing chemical operations. These units are nearly always excellently engineered, are usually made of high-quality materials, and are frequently available at a much lower cost than equipment designed specifically for a particular operation.

Although industry is not often influenced by style, the appearance of equipment may also be a feature in its selection. Cleanliness and ease of maintenance are often associated in modern streamlined designs.

Sources of Engineering Information

In order to use any check list effectively, the chemical engineer will be required to search for and assemble much information about the task, the materials, and the economic and other requirements which will influence his decisions. Consequently, it is useful to list the sources of information available to the engineer.

1. His own experience, academic and industrial
2. Classified information in handbooks and formularies
3. Textbooks, probably those used in university work
4. Other sources of classified information such as International Critical Tables, etc.
5. Books on the subject (monographs)
6. U. S. Government documents
7. Bibliographies (There are several bibliographies of bibliographies)
8. Periodicals
 - a. Abstracting journals, e.g., *Chemical Abstracts*, etc.
 - b. Technical journals such as *Industrial & Engineering Chemistry*, *Chemical Engineering Progress*, etc.
 - c. Trade magazines, such as *Paper Trade Journal*, *Petroleum Refiner*, etc.
 - d. House organs
9. The Chemical Engineering Catalog
10. Manufacturers' individual catalogs
11. Patents
12. Confidential reports of employing company
13. Experience of associates
14. Laboratory experiment

First establish *what*, then determine *how*! "How much?" or "how large?" follows from the handbook and calculating machine.

SECTION I

ASSEMBLY OF MATERIALS

1 : INTERPLANT TRANSPORTATION

Types of Transportation Systems

General Features of Transportation Systems

Water transportation

Rail transportation

Truck transportation

Air transportation

Pipe lines

Belt conveyor systems

Cost Summary

The type and relative cost of various transportation facilities exert a profound influence on plant location, and sometimes on plant construction; the capabilities of transportation equipment may exert an equally profound influence on plant design and plant operation. Consequently, the chemical engineer should have within his immediate knowledge a grasp of the major features of long-distance transportation of chemical materials.

The choice of a mode of transportation for interplant movement of materials is more likely to be governed by the location of a plant and of material sources and markets than by any other factors. In many situations, plant location is the direct result of the availability of low-cost transportation facilities. Other important factors are:

1. Nature of material to be transported
 - a. State: solid, liquid or gas
 - b. Sizes of solid materials
 - c. Types of container, if packaged
 - d. Effects of temperature, moisture and atmosphere
 - e. Hazards inherent in material
2. Quantities of material to be shipped
3. Value of material per unit of weight or volume
4. Cost of packaging

5. Distance to be moved
6. Location and type of shipping and handling facilities
 - a. At shipping point
 - b. At receiving point
7. Speed of movement required.

TYPES OF TRANSPORTATION SYSTEMS

The types of transportation systems available for interplant movement of materials are as follows:

1. Water transportation
 - a. Oceanic
 - aa. Transoceanic
 - bb. Intercoastal
 - b. Inland waterway transportation
 - aa. Lake
 - bb. River
 - cc. Canal
2. Rail transportation
 - a. Freight
 - b. Express
 - c. Parcel post
3. Truck transportation
 - a. Common carrier
 - b. Leased, owned or otherwise controlled for exclusive use of individual shipper
4. Air transportation
5. Pipe lines
6. Belt conveyor systems.

GENERAL FEATURES OF TRANSPORTATION SYSTEMS

Water Transportation

General. Water transportation is an exceedingly important means of traffic movement. Its cost per unit weight-distance (ton-mile) is so much lower than any other transportation service that it is to be preferred in every case where plant location and other conditions will allow it. The availability of water transportation has been the dominant factor in the extensive

industrial development in such areas as those surrounding the Great Lakes and along all coastal areas, and has been an important factor in the growth of cities like Memphis, Cincinnati, St. Louis, and other industrial centers on the Mississippi and Ohio waterways.

Water transportation, in addition to its low cost, is characterized by the handling of large tonnages of bulk material over reasonably long distances at comparatively low speeds. Transportation by rail or truck is usually preferred where tonnages are small, material is packaged or rather fragile, distances to be moved are short, or speed is essential.

As important as water transportation is, its adoption sometimes imposes difficulties, particularly in the matter of plant location. Shoreline areas which are of proper character for plant location, even along lakes or rivers, are somewhat limited. For a plant to use water transportation effectively, the carrier must be able to dock in a protected area adjacent to its warehouses. Not too many areas in their natural state provide this facility, even for shallow draft barges and river boats. Furthermore, the Atlantic and Gulf Coast areas are swampy in many localities for some distance back from the seacoast, and similar conditions are found along great stretches of the river systems. This partially submerged land makes the construction of the heavy foundations necessary for industrial buildings very costly.

Where shorelines are not low, they are likely to be mountainous or very rough, giving little level area for the construction of plant facilities. Much of the Pacific Coast is of this character, and where several excellent harbors do exist, suitable industrial waterfront property is limited and commands a very high price.

Ocean Freighters. The average chemical or process plant engineer will be concerned most with tankers, general-purpose cargo vessels, or refrigerated cargo vessels. Other special-purpose vessels, such as the floating fish-oil refineries, are limited in number and completely specific in function.

The *tanker* is, in most cases, a single-commodity vessel, that commodity being usually either crude or refined petroleum. It is designed specifically for carrying liquids, and it provides the cheapest form of long-distance transport. Indicative of the rela-

tive importance of water freight for the movement of petroleum is the fact that well over half of the total accumulated haulage of American petroleum is by water; the bulk of this is moved by intercoastal tanker service between Texas and Louisiana ports and points along the Gulf Coast and the eastern seaboard.

The capacity of one of the newer tankers may be as much as 10,000,000 gallons; the speed is in the range of 13 to 18 knots. These tankers are easily filled and emptied by pumps, and with



(Sun Shipbuilding and Dry Dock Co.)

Figure 1. S/S Cimarron, High-Speed Tanker.

proper dockage facilities, a tanker can either load or unload its cargo in a reasonably short time. Indeed, even a dock is unnecessary, as many tankers can be filled while lying several hundred feet offshore by means of oil-loading hose, which is plugged at the exit end and dropped back to the bottom after use.

Tankers are also used for transporting such commodities as molasses, solvents, and liquid caustic.

While there are a number of variations in the style of the *general-purpose cargo vessel*, the ship is merely a floating hull divided into a number of compartments or holds, the walls between them giving the ship torsional stability.

Unless the ship is engaged in one-product transportation, the carrier handles a miscellaneous cargo on every trip. This means that all cargo, except that carried as ballast in holds near the bottom of the ship, must be crated, packaged, or otherwise prepared for stacking in piles with other freight. Crating is expensive, and when this cost is added to that of stevedoring and stowage,

as well as of transportation, the total is often enough to discourage water shipment, especially when the loading point and destination are not too far apart and are joined by land transportation systems.

Cargo-carrying capacities of these vessels vary between about 7,000 and 15,000 long tons. Volumetric capacity is also important. Most freighters will hold approximately the same number of measurement tons (40 cu. ft.) as their long ton deadweight capacity.

The gross register tonnage of an ocean freighter is the entire internal cubic capacity of a ship expressed in register tons of 100 cubic feet each.

Refrigerated carriers are used for handling perishables such as fruit and meat. Although they are important in their particular trade, they are of limited interest to the engineers in most of the chemical or process industries.

Lake Freighters. The average lake freighter is a general-purpose vessel, and therefore resembles the general-purpose ocean freighter. However, it is much more likely to be in a one- or two-product service and its cargo is usually loaded, shipped, and unloaded in bulk. The modern lake freighter generally has a somewhat larger freight capacity, is longer, is much lighter in construction, is somewhat slower, is of shallower draft, has a smaller superstructure, and spends much less time in port during the shipping season than its ocean-going counterpart.

Most lake freighters haul cargoes of coal, iron ore, or grain, although a considerable number are in miscellaneous freight service. Since the haul is short in most cases, since loading point and destination are almost always connected by land transportation systems, and since the same expense is involved in handling miscellaneous freight on lake freighters as on ocean-going vessels, a much smaller proportion of the total freight is handled in lake freighters as miscellaneous cargo than in general-purpose ocean freighters.

The major disadvantage of the Great Lakes shipping is that for five or six months of each year ice makes freight movement on the Lakes impossible. This compounds the problems of storage and handling in the plant, and certainly adds to the cost of freight shipment. Nevertheless, Duluth, Minnesota is one of the major

ports in the United States from the standpoint of freight tonnage, and the Sault Ste. Marie Canals annually handle more freight tonnage than any other canal system in the world.

River and Canal Boats. The bulk of the freight which moves over the inland waterway systems is handled in flat-bottom.



(Foster Wheeler Corp.)

Figure 2. S/S Henry G. Dalton, Lake Freighter.

shallow-draft barges, normally grouped in rafts of 2 to 8 barges and towed or pushed by a shallow-draft river steamer. The modern barge is of steel construction, and holds from 500 to 2,750 tons of cargo. Navigable channels, suitable for barge movement, extend from New Orleans to Minneapolis and Chicago on the Mississippi and Illinois River systems; from Cairo to Pittsburgh along the Ohio River; from its mouth up to about Knoxville, Tennessee, on the Tennessee River; from St. Louis to Omaha on the Missouri River; and shorter distances on the Columbia, Willamette, Hudson, Fox, Warrior, Monongahela, and many other streams.

What amounts to an inland waterway extends along sheltered

shores, sometimes meandering miles inland from one coastal lake to another, along the Gulf of Mexico from Corpus Christi, Texas, to St. Marks, Florida. This is known as the Gulf Intercoastal Canal. Another similar canal extends northward from Florida along the Atlantic Seaboard. Several other navigable waterways, either natural or dredged, such as the Columbia and St. Lawrence Rivers and the Houston Ship Channel, allow passage of deep-draft ocean freighters and have, in effect, made seaports of inland cities.

The inland waterway system was at one time an important artery of commerce between the many industrial centers; for a time it almost completely disappeared, but within the past twenty years it has been revived.

Rafts. Some note should be taken of the practice of forming large rafts of sawlogs and towing them from logging operations to the sawmills. Similar possibilities are suggested whenever the material to be handled floats with ease.

Rail Transportation

General. The vast network of railroads provides a wide opportunity for plant location. Furthermore, railroads handle smaller lots more effectively than does any type of commercial water carrier, are less likely to damage fragile material, and usually make deliveries more rapidly.

In addition to their ability to offer shippers the advantages of a mass transport system, American railroads also provide several other advantages which may be listed as follows:

1. They can supply a variety of equipment to accommodate nearly every type of shipment from small articles to heavy units, such as chemical plant equipment.
2. They provide convenient facilities for loading and unloading expeditiously, such as sidings, loading and unloading platforms, ramps, and switching yards.
3. Any one railroad is not limited in equipment to that owned by itself, but can rent equipment belonging to other railroads.
4. Each railroad controls its own roadbed and, if necessary, can clear the tracks for through freight movements.

5. Freight movement via railroad is frequently within the control of railroad authorities alone, thus permitting uninterrupted service.

6. Rail transportation is usually less affected by conditions of terrain and weather than other types of transportation.

Though often not as obvious as the advantages, the disadvantages of rail transport must also be considered in the selection of a transportation system. Some of these disadvantages are:

1. The rates are higher than those of an all-water carrier.
2. Railroads usually operate on definite schedules which may not always suit the demands of the shipper. Trucks can load and depart as required.
3. In order to obtain minimum rates by rail, full carload shipments must be made. Less-than-carload (L.C.L.) shipments mean added expense and inconvenience.
4. Many items which can be shipped uncrated by truck must be crated for rail shipment.

Rail schedules are quite slow, considering the actual speed of the trains while they are moving. For years rail shipments averaged about twenty miles per day while in transit, but this mileage has lately been increased to somewhat more than double this figure, and many fast special freight services cover much greater distances. Competition from other carriers (truck transport will average in excess of 400 miles per day) and equipment shortages have necessitated this speed-up of service. It has been accomplished through the introduction of higher-speed locomotives, better constructed freight cars, and more rapid classification of cars in the transfer yards.

Rolling Stock. The "Official Railway Equipment Register" contains the dimensions, capacities, and classes of rolling stock owned by and operated over the railroad systems of the United States. The variety is great. As a result of many years' experience, the railroads have developed freight cars suited to all normal shipping needs. Even where no standard piece of equipment will suffice for meeting special requirements, improvisations using standard equipment can usually be devised.

Railroad freight cars can be divided roughly into two general types: those for handling solids or packaged liquids, and those for handling liquids. No freight car is available for handling material in a gaseous state. When it is required to transport a nonliquefied gas, the shipping unit is normally a general-purpose car to which gas cylinders may be attached.

Freight cars for handling solid materials: Some of the more common railroad freight cars are as follows:

- | | |
|---------------------|-----------------------------|
| 1. Flat cars | 4. Box car |
| a. Flat bed | a. General purpose |
| b. Well hole | b. Special purpose |
| c. Depressed center | 5. Stock cars |
| 2. Gondola cars | 6. Poultry cars |
| a. Flat bottom | 7. Refrigerator cars |
| b. Self cleaning | 8. Other special cars |
| 3. Hopper cars | a. Container car for L.C.L. |
| a. Open | shipments |
| b. Covered | |

Of the freight cars for handling solids, the one in widest use is the ordinary box car, which is merely a wood-lined steel box. Its major advantages are that (a) being standard, it is immediately available at most shipping points; (b) the contents can be protected from both weather and theft; (c) package freight can be readily packed in the car, and handled in and out without damage; and (d) less-than-carload (L.C.L.) shipments of miscellaneous freight can be accommodated.

Its disadvantages are (a) the narrow side entrance and the consequent impossibility of getting certain items in and out; (b) the difficulty of unloading bulk materials; and (c) the possibility of contaminating the floor or walls by chemicals and the necessity of deodorizing or decontaminating the car before reuse if so contaminated.

Many of the materials used and produced by the chemical industry are bulk in character, for example, salt, coal, limestone, sulfur, soda ash, salt cake, etc. All these are handled most cheaply by power machinery; as a consequence, gondolas, or preferably, hopper cars are more useful than box cars for this type of

service. The major disadvantage of the ordinary flat-bottom gondola cars, as compared to hopper cars or self-cleaning gondolas, is that materials must be lifted out of the car to be unloaded. The necessity of exposing the material to the weather en route may be overcome on the hopper car by installing a weather-tight roof. Such a roof is not possible, of course, on the



(The Denver and Rio Grande Western R. R. Co.)

Figure 3. Closed Hopper Car.

flat-bottom gondola, although at times tarpaulins or other temporary coverings have been used.

Another difficulty with the gondola or open-top hopper cars is the fact that during transit in winter, the contents of the car may become wet and then freeze to an almost solid mass. The consignee may not have facilities for warming the contents and may be helpless in attempting to empty the car. Even with steam and a warmed area in which to place the car, it may take hours to loosen the contents.

The flat car is of little interest to the ordinary manufacturer of chemicals; about the only large scale use is for handling pulpwood and saw logs. It does have considerable interest for the manufacturer of chemical equipment in that heavy and bulky equipment is most easily loaded on this type of car. Further,

the ease of unloading from this car is of even greater importance, since field construction crews receiving the loaded cars seldom have the heavy lifting and moving equipment which is available in the fabricating shops. Caution must be exercised in loading equipment or material of any sort on flat cars to see that it is securely fastened to the bed of the car and that it does not project beyond the sides of the car, or above a maximum height. Serious railroad accidents have resulted from failure to observe these precautions.

Insulated and refrigerated cars have interest for those industries engaged in the procurement of material which must be kept at constant temperatures during shipment. Most of the refrigerator cars are used in shipment of perishable food products.

The container car for L.C.L. shipments represents one of the attempts made by the railroads to meet truck competition for the transportation of less-than-carload lots of material. This car has not been too successful, although it does satisfactorily meet requirements insofar as the transportation of materials is concerned.

Tank Cars (for liquid materials). Tank cars, with the exception of the general-purpose tank car used widely in the movement of petroleum, are usually custom-built for special service. Consequently, the number of varieties of tank cars is large. Some of the more common variations are tabulated below:

- | | |
|---------------------------|-------------------------------|
| 1. Style | a. Low (standard) |
| a. Single unit (standard) | to |
| b. Multiunit | b. High (Over 300 psi) |
| aa. Nondetachable units | 5. Covering |
| bb. Detachable units | a. Uninsulated (standard) |
| 2. Unloading arrangements | b. Insulated |
| a. Top unloading | c. Superinsulated |
| b. Bottom unloading | (for liquefied "fixed" |
| 3. Capacity | gases) |
| a. Small (6,000 gal.) | 6. Means for heating contents |
| to | a. None (standard) |
| b. Large (12,000 gal.) | b. Internal coils |
| 4. Pressures | c. External coils |

7. Materials of construction
- | | |
|-----------------------------|------------------------------|
| a. Steel (standard) | lead, tin, stainless steel, |
| b. Stainless steel | glass, plastic, copper, |
| c. Aluminum | resin, etc. |
| d. Copper | f. Other special metals, al- |
| e. Steel lined with rubber, | loys and corrosion-resist- |
| | ant materials |

Since most of the reasons for the various types of construction are rather obvious, little need be said about the tank car beyond a discussion of some of the special uses or faults of the several variations in construction.



(General American Transportation Corp.)

Figure 4. Standard Low-Pressure Tank Car.

The ordinary commercial tank car is constructed of steel of sufficient thickness to withstand the mechanical shocks while the car is in transit; if necessary, it will sustain a pressure of as much as 5 to 10 psi above atmospheric. The capacity depends to some extent upon the density of the liquid which is to be shipped, being determined by the weight-carrying capacity of the car.

The steel tank car is perfectly satisfactory for handling liquids which are reasonably noncorrosive. If the liquid is corrosive toward steel, or if it will acquire a flavor, odor, or color by contact with steel, a corrosion-resistant material is a requirement. This is the sole reason for the several materials of construction, or for the application of chemically stable lining

materials. Milk, for example, is very sensitive to the materials of construction of the container, and is handled almost exclusively in glass-lined cars. Because of its corrosive character, hydrochloric acid is transported in rubber-lined cars. Many other similar requirements are met by the several materials of construction.

Gases such as chlorine, sulfur dioxide, propane, butane, and others whose critical temperatures are above normal atmospheric temperatures and which can be kept liquid by the application of pressures up to 200–300 psi, can be shipped in heavy steel (high-pressure) tank cars.

A recent addition to the line of tank cars is the car designed to haul, in a liquid state, the so-called "fixed" gases, such as nitrogen and oxygen. This car is, in effect, a tank-car-size Dewar flask which is so well insulated that vaporization of the contents proceeds very slowly. It is the slow vaporization which keeps the temperature of the contents at its boiling point. Under normal conditions, a car containing liquid oxygen at temperatures lower than -300°F . will arrive at its destination after being in transit for several days with 80 to 90 per cent of the gas still remaining in the car. This method of shipment is a great improvement over the shipment of these gases in the gaseous state merely under high compression. In the latter case the payload of gas rarely exceeds 10 per cent of the total weight of car and containers.

The necessity for steam coils is obvious in the case of cars designed for handling heavy fuel oils, molasses, coconut oil, road oils, and similar materials. Of considerable interest is the car designed for hauling materials which are normally solid, but have a low enough melting point to be handled in and out of the car as a liquid. Sodium and phosphorus are materials which are adapted to this method of handling.

Multiunit cars have proved their value in handling L.C.L. shipments of liquids. The multiunit car may be either a multi-compartment tank, or several small tanks. The latter construction is somewhat more expensive and cumbersome, but does permit the removal of one or two full containers and the replacement of these with empties from a former shipment. The re-

mainder of the car can then be forwarded to other users. A flat car with space for 12 to 15 one-ton containers for liquid chlorine is a type of removal-unit, multiple-unit tank which is commonly encountered. The multicompartment car has a dome and unloading valves for each of its several compartments.

Another type of tank car also having multiple domes is the so-called "dry flow" car, on which the several domes provide filling points for granular materials. This permits the car to be filled almost to the top with the solid. The material is usually removed from the car by dissolving it out with the solvent in which it is to be used. Dry shellac is often transported in this manner.

The bottom unloading arrangement of a tank car is most convenient for the user. The car, after being spotted in the proper location at the user's plant, can be drained by gravity to a tank at a lower level. When unloading through the top, the contents of the car must be removed by pumps or by siphoning. Interstate Commerce Commission rulings, however, prohibit the use of bottom-unloading tank cars in the transport of many liquids which are highly flammable, toxic, or otherwise dangerous if accidentally discharged along the railroad right-of-way.

Railway Car Capacities. Actually there are no "standard" dimensions of commercial railway cars. The majority of the box cars are 40-42 feet in length, about 8 1/2 feet wide and 9 feet in height (volume approximately 3,100 cu. ft.). Weight-carrying capacity ranges from 30 to 50 tons. Gondolas hold up to 70 tons with about 1,900 cu. ft. capacity. Tank cars are built to transport up to about 50 tons of liquid. Capacities, as indicated, range from 6,000 to 12,000 gallons.

Railway Car Ownership. The ownership of most ordinary freight cars is vested with the railroads.

Refrigerator cars are frequently owned by the shipper, or jointly by the shipper and the railroad. They are also owned and maintained by one of the several large car rental agencies, and leased on an exclusive usage basis to the shipper. The major reason for the controlled ownership arrangements of refrigerator cars is to prevent their use for any other service than that to which they have been assigned. Since these cars are used almost

entirely in transport of fresh foodstuffs, contamination by miscellaneous freight might make further use of the car by the food processor impossible.

Tank cars are owned either by the user, or by one of several large tank car renting and servicing organizations. One corporation regularly advertises that its fleet comprises more than 37,000 tank cars of 207 different types. These cars are usually rented on a monthly basis, although at least one company rents on a mileage basis. With a general shortage of rolling stock at the conclusion of the last war, some railroads undertook to build tank cars, and there are a few railroad-owned tank cars in service.

Other Railroad Equipment. In addition to rolling stock and trackage, the railroads provide facilities for rendering other necessary services required in the transport of freight. Among these are complete terminal facilities, switching yards, loading and unloading platforms, and sidings. The railroads maintain facilities for icing refrigerator cars and for resting, feeding, and watering livestock in transit. At certain ports they provide lighters and car floats for movement of shipments across water, and in connection with such services, maintain covered and open docks and piers. They own track scales and special equipment for loading and unloading, and provide a variety of services sufficient to handle nearly any type of shipment.

Express and Parcel Post. Except for small packages of chemicals, the additional speed of transit is seldom enough to justify the added cost of express or parcel post. Further, both types of shipment necessitate special preparation, and like freight shipments by rail, are carried on a prearranged schedule.

Truck Transportation

As has been previously pointed out, under certain conditions the transportation of material by motor truck offers distinct advantages over rail or water transportation but usually at a higher ton-mile cost. A more complete list of the advantages is as follows:

1. Except for premium rail shipments, and especially for short distances, the movement of freight can be completed

more rapidly by motor transport than by rail. Motor vehicles can normally be assembled, loaded, and moved more rapidly than railroad cars.

2. The schedule for motor vehicles can be easily arranged to fit the needs of the shipper.

3. Shipment of miscellaneous freight in L.C.L. lots is facilitated by the fact that the truck is a smaller unit than the freight car.

4. Motor transportation usually reduces the cost of crating, dunnage, blocking, strapping, loading, and unloading of supplies. This reduction in packing requirements results from easier handling due to the pneumatic tires, shallower loading within the cargo space, and freedom from the jars of switching cars in railroad yards. Loading and unloading is expedited because the truck can move readily between different warehouses to unload miscellaneous freight. Freight cars would be delayed in similar movement because of the requirement for switching.

5. Motor carriers normally pick up freight at the shipper's plant and deliver it to the door of the consumer. This service is included in the shipping rates.

6. Motor carriers are less hampered in their movement by accidents along the highway than are railroads by damage to or on its roadbed. They have more flexibility of routing.

7. There are some 49,000 communities in the United States which have no rail service.

In addition to its higher cost, truck transportation has other disadvantages as follows:

1. The highways over which motor transport moves are not controlled by the carriers. If the shipment is to move through several states, varying shipping regulations may add difficulties to the movement of freight.

2. The radius of operations of highway carriers is limited to the scope of their certificates and permits. Since truck transport equipment is not interchangeable as is rail equipment, shipments made for long distances may have to be unloaded from one truck and reloaded on another, possibly several

times, en route. This transfer of material often causes delays comparable to those caused by slow classification of cars in railroad yards.

3. Traffic congestion in heavily populated areas often creates bottlenecks which delay shipments. Railroads usually have clear rights-of-way.

4. Highways are more subject to weather interference than railroads.

5. Highways are sometimes not suitable for all types of traffic. Weight regulations may, for example, prevent the movement of many heavy units over highways when these same units can be satisfactorily moved by rail.

Highway Freight Equipment. The virtual standard unit of highway transport is the semi-trailer. This type of vehicle is towed by a tractor which may be separated from the trailer by the use of special jacks. This allows one tractor to be used interchangeably with a number of trailers and permits a more efficient use of equipment and personnel. This equipment has somewhat better maneuverability than the standard truck-trailer combinations, and because of its shorter length, is more likely to meet the several state highway regulations relating to vehicular length. Trucks in which the power and cargo unit are inseparable are also widely used. Truck or semitrailer bodies may take any of the forms suggested by the various patterns of railway equipment.

The capacity of trucks is from 5 to 40 tons, with the maximum gross weight being regulated by law in each state. The length, width and height of trucks or truck-trailer combinations are also regulated by statute.

Air Transportation

The transportation of chemical materials by air is limited to those which are so perishable this may be the only possibility, or so expensive that the added transportation costs do not materially affect the selling price. Many of the newer drugs are often shipped by air.

Air express, like rail express, usually moves on a schedule to which the shipper must suit his shipping time. Air transport is

also available on much the same basis as truck transport, providing the shipment is of such a size that the charter of the plane can be justified. The material for shipment by air must ordinarily be crated or packaged in much the same manner as if it was to be sent by railway or truck.

Pipe Lines

The movement of liquids and gases through pipe lines is highly specialized and extremely important. Were it not for the gas pipe lines, the movement of large volumes of gases over great distances would be an economic impossibility. The liquid pipe lines, used mostly for either crude or refined petroleum, and for water, are an important part of the general transportation system. Pipe-line transportation has these general characteristics: (a) one-material or class of material service, (b) fixed loading point and terminus, (c) high initial investment, and (d) the lowest ton-mile cost for overland transportation.

The petroleum and gas pipe-line system in this country, at the beginning of 1950, had a total length of about 264,000 miles. Of this figure, about 51 per cent is liquid line, the remainder gas.

Pipe-line size is governed by the amount of material to be transported through the line. Lines may vary anywhere from a diameter of 3 or 4 inches for the liquid collection lines to 48 inches for the gas trunk lines. The oil lines tend toward the smaller sizes, the gas toward the larger.

Pumping and storage facilities are located at convenient intervals along the right-of-way. This interval varies with the material passing through the line and the pressure maintained. With better pretreatment of petroleum in the field to reduce viscosity and with the higher pressures being used, it is now standard practice to place pumping stations as much as 75 miles apart. Pumps at these stations are usually driven by electric power if it is available at a reasonable price. Where electric power is not conveniently available, it is usually the practice to drive the pumps by diesel or gas engines which take their fuel from the pipe line.

Often overlooked in the transportation of materials by pipe line is the huge extent of pipe line which is required to collect, transport, and deliver water for domestic and industrial use. For most industries the importance of the correct placement and ade-

quate maintenance of these lines to give uninterrupted service cannot be overestimated.

The pipe line, once installed, offers the cheapest method of transporting petroleum and natural gas, and certain other liquids and gases such as water, chlorine, hydrogen, and steam, and solids such as powdered fuel, between points separated by land only. The cost of the operation of a line is low. Barring accident, a crew of 50 men can readily operate and service as much as 250 miles of line.

Belt Conveyor Systems

In recent years, the length of belt conveyors (actually, a number of belt conveyors arranged in series) has been increased so that at the present time many belt conveyors several miles long are in use. There is no reason why conveyors up to several hundred miles in length should not be completely successful, providing they meet the general requirements for their profitable use. Such a conveyor system was recently proposed, but plans have been suspended indefinitely pending legislative approval. The use of a belt conveyor for the transportation of solids over long distances would create problems similar to the use of a pipe line for the movement of liquids or gases.

COST SUMMARY

Since cost is such a vital element in the selection of a transportation system, cost comparisons are essential. Actually an accurate comparison of the costs of the various types of transportation, because of different types of commodities, different commodity rates, territorial differences, and many other factors is quite difficult. The following approximations give some idea of the relative costs of the several types of transportation.

TYPE OF TRANSPORTATION	COMMODITY	COST/TON MILE
Tanker, Ocean	Petroleum	\$0.00063
Freighter, Lake	Iron ore, coal, or grain	0.002 to 0.003
Barge, River and canal	Bulk materials	0.0045
Pipe line	Petroleum	0.00477
Rail tank car	Petroleum	0.01640
Truck	Petroleum	0.04873
Air	Miscellaneous	up to \$1.00 or more

2 : INTRAPLANT TRANSPORTATION

Techniques for Moving Solids

- Hand-powered intermittent moving devices

- Mechanically or electrically powered intermittent conveyors

- Mechanically or electrically powered continuous conveyors

Techniques for Moving Liquids

- Liquid pumps

- Pipe

- Valves

Techniques for Moving Gases

- Gas pumps

It was once almost standard practice to design a chemical plant to occupy a multi-story building, to elevate all the raw materials to a floor or floors near the top of the building, and to handle the materials from there by gravity. New and better equipment for moving hot solids, corrosive liquids, and numerous other difficult-to-handle materials have helped to get chemical plants out of the attic and place them in easily accessible, light, and airy factory buildings.

Dusts have been reduced, danger of spillage from broken valves or corroded pipes has been minimized, and plant conditions and housekeeping, in general, have been vastly improved by the development of dust and vapor-tight, corrosion-resistant, and mechanically-improved equipment for the movement of chemical materials.

As a check list to be used in the selection of the best type of transportation to meet any problem involving the short-distance movement of materials, the following are some of the more important points to be taken into consideration:

1. Nature of the material to be handled
 - a. Solid

- aa. Size of individual pieces
- bb. Fragility or hardness
- cc. Density
- dd. Packing, loose or solid
- b. Liquid
 - aa. Presence of sand, grit, mud, etc.
 - bb. Viscosity
- c. Gas
 - aa. Corrosive properties
 - bb. Presence of dusts or fumes
- 2. Temperature of material to be handled
- 3. Corrosive properties
- 4. Amount of material to be handled, total and peak loads
- 5. Directions of movement required
- 6. Cost of equipment: initial, maintenance, operation
- 7. Flexibility of equipment
- 8. Construction characteristics of building and requirements of installation
- 9. Necessity for maintaining continuous supply, or possible desirability of intermittent supply
- 10. Ease of loading or unloading
- 11. Toxicity, flammability or other hazards involved in handling
- 12. Importance of freedom from contamination; ease of cleaning

Of the many techniques available for the transportation of materials, the simplest classification is a division between those used to handle solid materials and those used to move liquids or gases.

TECHNIQUES FOR MOVING SOLIDS

The techniques for handling solids may be divided into intermittent and continuous methods. In methods classified as intermittent, the device has only one container which must be filled and transported to the discharge point, emptied, and returned to the filling point before it can carry a second load. Continuous conveyors are those which, in general, have filled containers or space for material continuously moving to the dis-

charge point while empties are being returned, at the same speed, to the charging point.

A further sub-classification of all moving equipment, either intermittent or continuous, relates to the direction of movement. Some conveying systems are designed to move material in a more or less horizontal direction, others vertically, and still others to convey loads in various combinations of vertical and horizontal movement.

A list of some of the more important methods available for handling solids is as follows:

1. Hand-powered intermittent moving devices
 - a. Shovel
 - b. Wheelbarrows, dollies, stevedore trucks, factory hand trucks, jack lift trucks, etc.
 - c. Hand hoists, jacks, drum hoists
2. Mechanically- or electrically-powered intermittent conveyors
 - a. Essentially horizontal movement
 - aa. Windlass
 - bb. Industrial truck
 - cc. Industrial railroad
 - dd. Cableway
 - ee. Monorail systems
 - b. Vertical movement
 - aa. Power hoist
 - bb. Elevator
 - cc. Skip hoist
 - dd. Stationary boom
 - c. Combination of horizontal and vertical movement
 - aa. Jib cranes
 - bb. Overhead cranes
 - cc. Traveling cranes
 - aaa. Gantry cranes
 - bbb. Wharf cranes
 - ccc. Shipbuilding and drydock cranes
 - dd. Mobile cranes and shovels
 - ee. Pneumatic conveyors
3. Mechanically- or electrically-powered continuous conveyors

- a. Horizontal movement
 - aa. Belt conveyor
 - bb. Roller conveyor
 - cc. Ball conveyor
 - dd. Apron conveyor
 - ee. Screw conveyor
 - ff. Drag or flight conveyors
 - gg. Chain or drag conveyors
 - hh. Sluice
 - ii. Vibrating conveyor
 - jj. Oscillating conveyor
 - kk. Carriers
- b. Vertical movement
 - aa. Bucket elevator
 - bb. Chute
 - cc. Vertical screw elevator
- c. Combination of horizontal and vertical movement
 - aa. Continuous drag conveyor
 - bb. Bucket elevator and conveyor
 - cc. Pneumatic conveyor
 - dd. Special types

Hand-powered Intermittent Moving Devices

Shovel. Human energy is by all measures the most expensive to use for the movement of materials, but there are conditions which warrant its use. For one thing, in remote locations, it may be available while power equipment or its fuel is miles away. Its use may therefore be a necessity. Even on a competitive basis, the man with a shovel is perhaps the most versatile of all moving systems, at least as far as being able to change locations readily is concerned. The initial cost of his equipment is negligible as compared to any power systems, the roadway or surface over which he moves can be lightly constructed, and though possibly quite rough, it will still be adequate.

Wheelbarrow, Dolly, and Truck. If the shovel is replaced by a wheeled unit, the conveying system at once gains considerable capacity, the power cost per unit of movement is decreased and heavier loads are possible with less fatigue to the prime mover. Simultaneously, some versatility is lost, a heavier

and smoother roadway is required, and both the initial expense and maintenance cost of the equipment are increased materially.

This comparison between the wheelbarrow and shovel is drawn chiefly to illustrate the fact that as there is a shift from the simpler to the more complicated in any type of equipment, versatility, low initial cost, and certain other advantages are very likely to be sacrificed for greater speed or capacity or both.

Hand-operated Hoists and Jacks. Hoists of many basic patterns are built for hand operation. In their use, the lifting capacity of a man or men can be greatly increased. Several styles of hand-operated jacks are available. These also give great mechanical advantage at a great sacrifice of speed. Many of these devices have been mechanized simply by the addition of an electric motor or gasoline engine to furnish the motive power required.

A number of other hand-operated conveying devices such as forklift trucks, hand elevators, and even continuous conveyors are also available. Most of these, however, have their power-driven counterparts.

Mechanically or Electrically Powered Intermittent Conveyors

Horizontal Movement. *Windlass.* A power-driven windlass on a vertical shaft is often used to draw cars along a track or for other similar service. It is normally fixed in location, but is useful in many instances.

Industrial Trucks. Of all the intermittent moving devices used in factory operations, the ones most often encountered are the low bed, short wheel-base, industrial trucks. Even without the self-loading feature of the popular fork-lift truck, the industrial truck is easier to load and has much greater maneuverability than an ordinary highway truck. The industrial truck consists essentially of two parts, the motive power and the truck body or bed.

Both electrically driven and gasoline-driven trucks are in use, the latter being used more extensively. At one time the electrically driven truck was quite popular; it is quiet, maneuverable, powerful, and quick to respond to the will of the operator. However, gasoline-powered trucks have today achieved operating qualities that are comparable to those of the electric truck, and have freed

the plant using these trucks from the necessity of installing, maintaining, and operating a storage battery-charging department.

It is in the platform, body, or lifting mechanism that these trucks are most likely to vary in design. Such trucks as fork trucks, fork-lift trucks, high-lift trucks, platform and platform-



(Towmotor Corp.)

Figure 5. Fork Lift Truck.

lift trucks, scoops, barrel lifts, roll loaders, and many other styles are available.

The fork truck and ordinary fork-lift truck are most widely used in chemical and other industry. Both the fork and lift types are provided with projecting fingers which can be lowered to within a few inches of the floor and which are designed to be run under a square or rectangular platform called a pallet, or skid platform.

The only marked difference between the fork truck, the fork-

lift truck, and the high-lift truck is that the first simply lifts or tilts the pallet enough to clear the floor; the fork-lift truck can be used to lift the load 4 to 6 feet off the floor; and the high-lift to a height of perhaps 12 feet. The lift designs permit the operator to stack and unstack palletized loads several tiers in height.

In the platform truck, a platform replaces the fork but the truck is otherwise much the same. A number of other trucks of specialized, or custom design are also available, such as the style in which the truck has a device to grasp a barrel or drum and hold it firmly while it is being moved.

Detachable trailers towed from place to place by an industrial tractor find wide use, and are of particular value where several truck loads may be accumulated before movement is necessary, or when the amount of material to be moved exceeds the amount readily carried in a single load.

Continuity of supply is often better assured by this type of vehicle in that a number of filled containers can be spotted at strategic locations and then be moved by hand to the actual position as required. The continuous removal of a product from an operation is likewise facilitated.

Industrial Railroads. In many cases it may not be profitable to construct and maintain floors or roadways heavy and smooth enough to support industrial trucks. There are many situations, therefore, in which the industrial railway has solved problems of transportation effectively and with reasonable efficiency. Notable use of this type of transportation is in mines, most of which are serviced by electrified railway lines.

Cableway. Where features of terrain or existing structures make it impractical to build a road or lay a railroad, or where the short duration of operations make permanent construction uneconomical, a cable can be suspended above and beyond the loading and unloading points and materials transported in containers suspended on a trolley free to move over the cable.

Many mines use this method for moving ore to concentrating plants or to the loading stations of more conventional means of transportation. The overhead cable and trolley is almost always used as a means of conveyance around large dam or bridge construction projects; it is frequently used in logging operations.

particularly in rough country, to move logs from the place where they are felled to a loading point on a railroad or truck line.

Monorail Systems. Many factories make very effective use of the monorail as a means of transportation within factory areas. It consists essentially of a traveler or trolley operating on a rigid overhead rail, and a power or hand hoist attached to the trolley to lift the load to be carried. The rigid rail system can be made to turn corners, and to travel up or down inclines, and it can be provided with means for switching from one rail system to another. The monorail is used in chemical plants, but its weight-carrying capacity is not large; for intermittent moving of bulk or packaged material other types of cranes or industrial trucks usually have been found to be more practicable.

Vertical Movement. The various types of equipment to which reference has so far been made have been concerned with movement of materials in an essentially horizontal plane, although most of the devices must lift the material a short distance to clear the floor or any obstructions in their path. There are a number of devices designed to move their loads in vertical direction.

Power Hoist. Any of the hand hoists, such as the block and tackle, chain fall, or winch can be mechanically powered to increase speed and capacity, and relieve the operator of arduous physical exertion. A number of styles of such power hoists are available. The power chain-fall is most adaptable to use when the hoist can be fastened to an overhead support; the winch is most useful when the power unit can be firmly anchored to the floor or ground.

Elevator. The ordinary industrial elevator is essentially a platform guided by vertical rails to keep it from swinging or tipping, and moved up or down by proper mechanical devices. Most of the elevators for industrial service are activated by a power winch. Many elevators are dual-purpose, that is, the elevator is used for both personnel and materials; when such is the case, the elevator requires such safety devices as magnetic brakes, snubbers, and safety gates, most of which may be omitted on an elevator used exclusively for freight.

Skip Hoist. The skip hoist is a variation of the ordinary industrial elevator in which the elevator platform is replaced by a



(Link-Belt Co.)

Figure 6. Skip Hoist.

container which will hold bulk material. Generally, the skip hoist uses an empty car traveling downward in another trackway to counterbalance the weight of the car being moved upward.

Skip hoists are operated on either vertical or inclined trackways. The first is the usual design, but the latter arrangement is necessary if the receiving bins must be placed directly below the discharge point of the skip hoist.

Stationary Boom. The stationary boom provides a simple means of lifting and supporting a load. Its use is limited, however, because it is restricted to loading from one fixed point.

Combinations of Horizontal and Vertical Movement. The usefulness of most moving devices can be markedly improved if their movement is not limited to one direction. As a consequence there are numerous moving devices designed to give this increased versatility. Most of these devices fall into the general

classes of cranes. Cranes may be roughly classified as those operating from a fixed position, those functioning over a fixed area, and those completely mobile with little or no limitation as to the location of their operation.

Jib Crane. The simplest of all jib cranes consists of a boom (the jib) which is hinged to a wall. The boom can move in a horizontal plane over an arc of nearly 180° . Greater versatility can be obtained if the boom is replaced by a steel I-beam on which a trolley hoist can be operated. The crane can thus operate over the entire area transcribed by the end of the boom, as it moves on the arc of the circle. If the rigid support of the jib is replaced by a mast or pillar which can be rotated through a full circle, the area of operation of the crane is doubled. This is a particularly useful crane for loading and unloading ships and railroad cars.

Overhead Cranes. The overhead type crane, with its large capacity and its ability to reach every part of a factory area, is the favorite with most manufacturers. This type of crane usually consists of a hoist, trolley, and traveling beam. The latter moves on elevated rails which are often supported on the opposite walls of the building in which the crane is to be used. The trolley supporting the hoist unit is free to move lengthwise on the traveling beam. The overhead crane is usually operated by three motors, one for each of the three movable elements. Each can be started and stopped independently at the will of the operator. Overhead cranes are widely used in factory buildings, and even out of doors for a large variety of moving services.

One of the main disadvantages of all overhead cranes is the danger to personnel or equipment under the crane while it is operating. This danger, however, can be minimized by careful operation and alert workmen.

Traveling Cranes. A number of cranes of various types are constructed to be operated over rails laid some distance apart on the ground. While theoretically, at least, smaller varieties of any of these cranes could be used indoors, actually few of them are. The overhead cranes can perform the same service without requiring working floor area in the factory building for the rails.

A popular traveling crane for handling bulk materials such as coal and ores is known as a *gantry crane*. It consists of a high

bridge, the ends of which are supported on heavy rail-mounted trucks. The span of the bridge may be as much as 300 feet. A trolley moves on the bridge. As with the overhead crane, this crane will reach any space between the rails throughout the full length of its travel, and on some designs will even reach outside the rails.

A somewhat lighter traveling crane is often used for wharf operations. The *wharf crane* consists of a boom or jib of more



(Whiting Corp.)

Figure 7. Gantry Crane.

or less conventional pattern mounted on a wide carriage which moves from end to end of a wharf on special rails. The boom on this crane is characterized by an extension jib which folds as the boom is raised, thus permitting close-in work. These cranes, as the name indicates, are used to unload vessels tied up along a wharf or dock.

A massive wharf crane designed to unload ore or coal rapidly is available at some lake ports. When time is at a premium, as it normally is where the movement of the ore carriers is concerned, these cranes are extremely useful.

A very heavy traveling crane is used in ship building and maintenance. These are mammoth cranes often having a lifting capacity of 350 or more tons.

Mobile Cranes. A number of cranes are available in which the crane carriage is capable of being moved over a standard road bed, such as a railroad or highway, or can be moved about over

land or water at the will of the operator. Carriages for these may be self-propelled or towed railway cars, motor trucks, caterpillar tractors (crawler types), heavy pontoons or feet (walking types), or either self-propelled or towed barges.

Lifting Devices. The types of devices which are used with cranes to engage and hold the load of material being moved are quite varied; these must be selected to best meet the requirements.

The simple *hook* is widely used as a lifting device. One or more hooks may be used to engage a bail or lifting eye attached to the load to be moved. Auxiliaries sometimes used with the hook are the slip noose or choke, and cable or net slings. These devices are designed to carry material in bags, packages, boxes, or other rigid or semi-rigid containers. In those cases when the material is in large units which are not damaged by relatively rough treatment, *grapple hooks* similar to ice tongs may be useful.

Many of the raw materials of the chemical industry and almost as many of its products are brought to the consuming plant and are handled by it in loose granular form. The most useful device for loading and lifting this material is the *clamshell bucket* which is lowered into the pile of material with its jaws open. The jaws, being heavy and reasonably sharp, sink into the pile. As the crane lifts the bucket out of the material the jaws close and hold the material in the space between them.

Piles made up of lumpy material, such as coarse rock or randomly piled cord wood, may resist the penetration of the clamshell bucket. This problem may sometimes be solved by replacing the two-leaved clamshell bucket by a finger-leaved *orange-peel bucket*. The leaves of this bucket are pointed and more like tongs than a bucket in character. However, they do penetrate piles of random-sized material more easily than does the clamshell.

Large tonnages of scrap iron are handled daily at numerous collection points and consuming mills. Because of random sizes and shapes, scrap iron is very difficult to handle by conventional lifting devices. The *electro-magnet* which can be energized at the will of an operator has proved to be a very satisfactory solution for this extremely difficult problem.

All the lifting devices described have been designed to be oper-

ated at the lower end of a non-rigid lift composed of suspended steel cables, chains, or ropes. The *shovel*, designed to be operated at the end of a rigid arm, is exceedingly important. Since shovels can be pushed or pulled into a pile by the application of a positive pressure, they are especially useful where digging is to be



Figure 8. Crawler Mounted Stripping Shovel.
Dipper 36 yd.—Wt. 2,850,000 lbs.

(Bucyrus-Erie)

combined with loading and lifting, or when large or random size rock may preclude the possibility of using a clamshell or orange-peel bucket.

Power shovels come in a number of different styles, the major distinction being in the direction of operation of the shovel. The usual arrangement for a power shovel is one in which the shovel is moved away from the crane in order to load it. On a ditcher or backhoe the bucket is inverted on its arm and is pulled toward the power unit. The main feature of this shovel is that it can work up close to the treads of the crane. The skimmer or dragline pulls or pushes the shovel more or less horizontally. The shovel of the skimmer is arranged to travel along a rigid boom which

holds it in position. The dragline pulls the shovel on a semi-slack cable.

Pneumatic Conveyors. There are a few conditions where pneumatic conveyors for intermittent service can be useful in a chemical plant. The system is similar to that employed by stores to send orders or messages from one department to another.

Mechanically or Electrically Powered Continuous Conveyors

Horizontal Movement. A conveyor synchronized to bring a continuous supply of raw materials or remove a continuous stream of finished product from a chemical process is a most useful device. Even in many cases where the process itself is batchwise in character, a continuous conveyor is still used, discharging its load into accumulator bins to await charging into the process, or removing the contents continuously from dump tanks which may be alternately full and nearly empty as process-vessel contents are discharged.

Belt Conveyors. Belt conveyors have an excellent record for service in the conveying field and are a very popular type of equipment. This conveyor, in its simplest form, is a continuous belt moving over closely-spaced idler pulleys. The belt is moved by means of a drive pulley located preferably at the discharge end of the top or run section; it is held tight by a fairly large diameter idler pulley at the far or tail end. Virtually all belt conveyors are provided with a charging hopper which prevents material from being thrown over the sides as it is loaded on the belt.

As efficient as it is, the simple belt conveyor does have some deficiencies in its operation, and many devices have been developed for overcoming some of them. Troughing idlers to form a shallow trough of the belt, belt tighteners, and guides to restrain sidewise movement of the belt are accessories incorporated as almost standard equipment to improve the operation of the conveyor.

The basic pattern of belt conveyor is arranged to discharge its material over the end as the belt passes around the drive pulley. It may, however, be necessary to discharge the material at one or more points along the line of travel of the belt. If the material being conveyed is pliable and wet so it will not damage the belt

if it is wiped across its surface, a blade placed at an angle to the direction of travel and raised to just clear the belt will roll or plow the material off the belt.

A traveling dump has been developed to discharge the material from a belt at any point in its run. It removes the belt from its normal supporting idlers and directs it up and over a roll where



(Link-Belt Co.)

Figure 9. Belt Conveyor.

it is emptied before being returned to its normal position. Not only can this dump be moved to any position along the belt and locked there until it is desired to move it, but it can be set to automatically move slowly back and forth from one end of the belt to the other. This type of operation is of particular interest to the mineral-smelting industries or to the fertilizer industry, where incoming materials may be blended into a large storage pile of average quality.

The belts normally used on a belt conveyor are made of rubber-covered fabric. If constructed properly, they give remarkably long wear. Where rubber is not satisfactory, neoprene or other

synthetics may replace the rubber; or the whole belt may be made of steel, either as a thin strip or chain belting. Many other improvements have been added to the belt conveyor. One has been a belt having tiny fingers on its face to improve the grip on the material and to increase the angle up which it may be carried. Another has been the addition of rubber scrapers to remove sticky material from the belt during its return run.

The belt conveyor is an efficient, low-cost, high-volume conveyor. With the improvements which have been made to overcome certain specific deficiencies in its operation, the use of this conveyor has become widespread. The belt conveyor is not satisfactory for use on materials which are highly variable in size. It is not usually satisfactory for large single pieces, such as saw logs nor for loose, light, and powdery substances. It cannot convey materials readily up a slope of more than 15° to 20° from the horizontal. The belt conveyor is not often portable; because of inertia of the load, it usually cannot be quickly started and stopped; it cannot easily be made to run in a reverse direction; it cannot turn corners; it is difficult to load properly; and it will frequently drop some of the material it is carrying. It is more expensive in short lengths than are some of the other types of conveyors. Virtually all other conveyors have been developed to overcome one or more of these deficiencies.

Roller Conveyor. The roller conveyor is simply a series of rolls lying in a horizontal plane; all or some of them are power-driven to move the material along the conveyor. A completely hand-operated roller conveyor is also available. It is used mostly because it is small and light in weight and can be easily moved into restricted locations. The rolls of the conventional roller conveyor often are studded or corrugated to give positive drive. The roller conveyor can be constructed to provide a change in direction through a sweeping curve.

The outstanding advantage of the roller conveyor is that it can be run with equal ease either forward or backward, and that it can be instantly stopped, started, or reversed. Further, since the rolls are spaced a small distance apart, transfer conveyors can be made to rise between them to lift the material off the conveyor. Another feature is that the rolls can be made to drive the material

against a stop and hold it there as other units are brought to the same destination, or until it is removed by a second conveyor.

It is obvious, of course, that the roller conveyor cannot be used for granular material or for any units too small to rest on at least three rollers simultaneously. It finds wide use in loading and handling boxes, for moving saw logs, in the movement of lengths of steel rail, pipe, structural shapes, and similar material.

Ball Conveyors. If the rollers of a roller conveyor are replaced by balls rolling in sockets which are mounted on a firm surface, a package or box having a flat bottom can be easily pushed in any horizontal direction. These are universally hand-powered, but make very convenient transfer stations for distributing material coming from one belt or roller conveyor to two or more conveyors leading away from the station.

Apron Conveyor. The moving belt of the belt conveyor can be replaced by steel bars or plates fastened at the ends to links of two endless chains. The driving force is transmitted by means of sprockets. These conveyors normally move much more slowly than do the belt conveyors, but they can be heavily loaded, and can be used successfully to handle materials at high temperatures. A conveyor of this general type, having massive bars for the bed, is used as a traveling grate in many modern industrial boilers.

Screw Conveyors. The screw conveyor consists of a spiral or helix attached rigidly to a shaft which is rotated in a U-shaped trough. Granular material is moved along the length of the trough. The screw conveyor has an outstanding feature: it cannot be overloaded. Regardless of the amount of material above the conveyor feed, only that portion which is held between the "flights" of the screw will be delivered with each turn. It is this feature which promotes its widest use—that of a feeding device. It is frequently used in conjunction with another conveyor to regulate the load of material delivered to the feed hopper of the second conveyor, and is often used for metering solids into a system.

Because of sag of the shaft, a single unit of a screw conveyor cannot exceed about 12 feet in length. Longer conveyors can be formed by placing bearings at 10- to 12-foot intervals along the shaft. While there is theoretically no limit to extension in this

manner, the bearings interfere somewhat with the smooth flow of material through the conveyor, and screw conveyors more than four or five sections in length are rarely used.

The screw conveyor will not handle pieces of large size or any material which would be damaged by the action of the screw. In addition to its use in handling dry granular solids, this machine will successfully transport sticky mixtures of solids and liquids.

Flight Conveyors. It has been pointed out that the ordinary belt conveyor is limited to small angles of inclination from the horizontal. If material is pulled along a trough by flat scraper blades, conforming to the shape of the inside of the trough, a considerably greater angle of inclination can be obtained. This is the principle of operation of the flight conveyor, and while it can ordinarily be substituted for the horizontal belt conveyor, it is most useful in the inclined position.

Since the material must be pulled through a steel trough, sliding as it goes, power requirements and maintenance costs are both likely to be quite high. Friction losses of the flights themselves can be reduced by suspending them from rollers. Standard patterns of the flight conveyor cannot easily move pieces of large size nor successfully handle fragile material.

Chain or Drag Conveyors. Large pieces of material can often be handled successfully if lugs or hooks can be made to rise through the bottom of a trough or through slots in the surface of a flat table. Horizontal chain conveyors, working in parallel gangs, will move material away from roller conveyors very effectively in a direction at right angles to the roller conveyor.

Chains are sometimes dragged in the bottom of troughs to move granular material. The material is moved by being caught in and on the chain links.

Sluices and Flumes. Sluices and flumes are specialized devices for the movement of solids in those cases where the solid can be suspended and moved in a liquid. These devices are open troughs, the bottoms of which have a definite slope from the horizontal. An advantage of the flume is its great simplicity and ease of operation. The large quantity of water required and the difficulties encountered by freezing in cold weather detract from its usefulness. Mixing of water and solid may be disadvantageous. The

beet sugar industry makes use of the flume in floating beets from storage into the factory.

Vibrating Conveyors. The vibrating conveyor, built for conveying materials a relatively short distance either horizontally or up or down a moderate incline, is used as a feeding device and, when arranged in series, as a conveyor. This conveyor may be either a tube or a flat-bottom trough, vibrated by means of an attached electric vibrator. This conveyor possesses two advantages—low maintenance costs and reduced damage to conveyed materials by mechanical working.

Shaking Conveyor. Material can be moved along a trough if the trough is given an endwise shake, faster in one direction than in the other. This is the principle of the shaking conveyor. It has advantages similar to those of the vibrating conveyor.

Carriers. Several manufacturers are producing conveyors in which the material is held in shallow rectangular buckets which are moved over rail supports. These conveyors give positive movement to a material such as is obtained in the flight or drag conveyor, but they avoid the high friction of those types.

Vertical Movement. Virtually all the horizontal equipment, e.g., belt conveyors, screw conveyors and others previously described, will move materials up an incline varying from a few degrees to as much as 30 degrees. Frequently, therefore, these machines are used as elevators as well as horizontal movers, and in many instances two pieces of equipment, or even two plants, are located far enough apart horizontally to allow the use of one of these conveyors working within its allowable angle of inclination. There are, however, several devices available for moving material in a vertical direction.

Bucket Elevator. The bucket elevator is much used for lifting material in a continuous stream. It consists of a number of small open boxes or buckets fastened to a belt or chains which pass over pulleys or sprockets at the top and bottom of the elevator. At the bottom the buckets dip into a "boot" receiving the material to be elevated. The buckets are filled as they dig through the material in the boot, and they discharge it into a chute as they are inverted in passing over the pulley at the top. Material is fed continuously into the boot at the approximate speed at which it is picked up by the buckets.

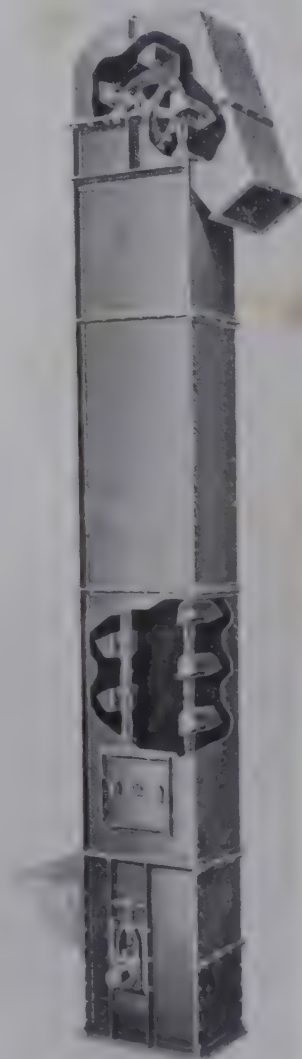
Bucket elevators differ somewhat in style depending on how closely the buckets are spaced on the belt, how they are attached to the belt, and how they are discharged. Elevators are either of the spaced-bucket type with buckets 12 to 18 in. apart, or the continuous-bucket type with the buckets as close together as their shape will permit. They are usually attached rigidly to the belt or chains, but may be swung from pins. The buckets may be discharged by centrifugal force or may simply drop their charge into a chute as they pass over the top guides.

One of the major operating difficulties of the bucket elevator is that caused by the jamming of materials between the buckets and the sides of the boot. The bucket elevator cannot successfully handle sticky materials, since the buckets will not discharge; nor can it handle material in which any lump is larger than one of the buckets. Wear and replacement are high. If operating area will permit, a belt or other inclined conveyor will often be more economical for elevating material a short distance.

Chutes. Material that is to be conveyed downward seldom requires power-driven conveyors, but it is rarely dropped any great distance.

Instead it is introduced into an inclined plane, or chute, and allowed to roll or slide to its destination at the bottom.

The chute is quite simple in design. It usually takes one of two forms—either a straight incline, or a vertical spiral. The latter design is more expensive, but it saves considerable space in allowing the material to move in a vertical downward direction.



(Link-Belt Co.)

Figure 10. Bucket Elevator — Spaced Buckets.

The use of a chute is not quite as simple as it may appear, however, since material has to be moved away from the discharge end of the chute or it will accumulate and prevent further discharge. Further, the chute must be carefully designed: if it is too steep it will give much the same effect as dumping the material, resulting in dusting, or damage to fragile material; and if the incline is too flat, the material will not slide over it.

Vertical Screw Elevators. If a screw conveyor is placed in a snugly fitting cylindrical housing and fed by positive means, it can be used effectively in a vertical position to elevate finely divided material, such as cotton seed, grain, cement, and lime. The maximum lift of such a conveyor is about 50 feet. Its application is limited to a rather small range of materials.

Combination of Horizontal and Vertical Movements. A number of methods of conveying materials in any direction have been tried. Of these, several have been markedly successful.

Bucket Carriers. To a limited extent, all the conveyors and elevators described are capable of moving material both horizontally and vertically. For example, several styles of bucket elevator can be carried around sprockets and operated as a horizontal conveyor as well as an elevator.

Continuous-Flow Conveyors. The continuous-flow conveyor consists of a totally enclosed tube, usually rectangular in shape, through which the material is pushed in a solid column or core by means of flight-like vanes or pushers attached to a continuous chain. The flights may cover only a small fraction of the cross section of the tube, leaving a large clearance between the flight and the wall. These skeleton flights do not push through the solid, but propel it ahead of them.

The movement in continuous-flow conveyors can be in any direction or combination of directions. They are slow-speed, but they have a fairly large capacity because of the totally filled tube. They are for the most part dust-free, and are susceptible to good feed control. Their use is limited, however, to fine and non-abrasive materials. They are somewhat more expensive than other types of conveyors if used for a horizontal or low-incline run.

Traveling Rubber Tube Conveyor. The Johns conveyor, one of the most novel of all types, consists of an endless rubber tube,

split lengthwise, and so arranged that it can be opened or closed by passing it over or through suitable mechanical devices. Thus the tube is filled while open; it is then closed, directed to the discharge point, opened for discharge of the contents, discharged, closed, and returned to its filling point. The tube, even when filled, can be passed around pulleys in any direction. This conveyor will handle both wet and dry materials, is dustless, will handle abrasives, and is almost noiseless in operation.

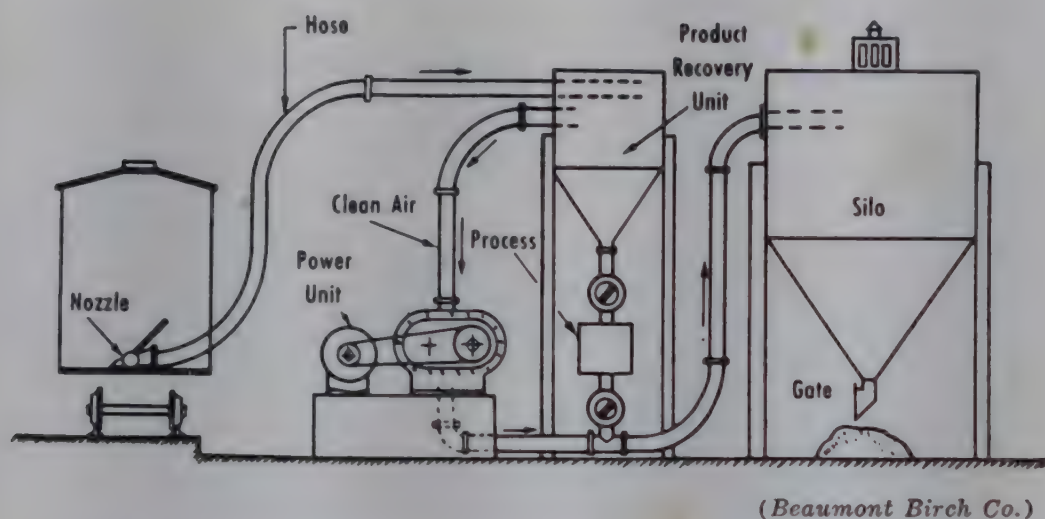


Figure 11. Pneumatic Conveyor. Schematic drawing.

A conveyor of similar principle has a rubber "zipper" closure. The tube of this conveyor is attached to a flat belt which can be carried over and around conventional pulleys.

Pneumatic Conveyors. Of all the continuous conveying systems, the pneumatic conveyor is most versatile with respect to the direction of movement. Solids which can be carried successfully in this conveyor are led horizontally, vertically, either up or down, up or down inclines, around corners, and over, under, or around obstructions with equal facility.

The conveyor is a large air system which is under either vacuum or pressure, or part vacuum and part pressure. It consists of four major elements: the conveyor tubing, the blower for moving the air stream, the receiving bin, and a dust separator. The solids are carried in the air stream.

The multi-directional flow of solid materials in a pneumatic conveyor is its outstanding advantage. If the intake of the con-

veyor is under vacuum, it has another very substantial advantage in that the position of the intake can be varied at will. For the latter reason the pneumatic conveyor is a very popular unit for such service as unloading bulk material from either railroad box cars or the hold of a ship. It is of particular interest if these materials happen to be toxic to workmen or create unusually hazardous or objectionable conditions because of dusts or odors.

The major disadvantage of this conveyor is that it will handle material only up to about one inch in diameter. The system is somewhat expensive to install, and its power consumption per ton of solids moved is likely to be considerably higher than the moving of solids on a belt or in a trough. Its use must, of course, be limited to materials which are not sticky.

TECHNIQUES FOR MOVING LIQUIDS

Since most liquids have similar general physical properties, the systems used to handle them are not as widely variable in pattern as are the solids conveyors. Further, with a few exceptions such as a bucket or drum, which are sometimes used for moving liquids, all liquid movement is done by systems capable of continuous delivery.

The conveying systems for liquids consist of three basic parts: (1) the pump for imparting pressure or head to the liquid; (2) the pipe or tubing and fittings to provide a channel for movement; and (3) the valves used for control.

LIQUID PUMPS

Pumps are manufactured in many styles, new designs and improvements on existing types continually being placed on the market. Most existing patterns of pumps can be roughly grouped into classes depending upon the method by which energy is imparted to the liquid. This general classification is as follows:

Centrifugal pumps

Volute pump

Diffusion or turbine pump

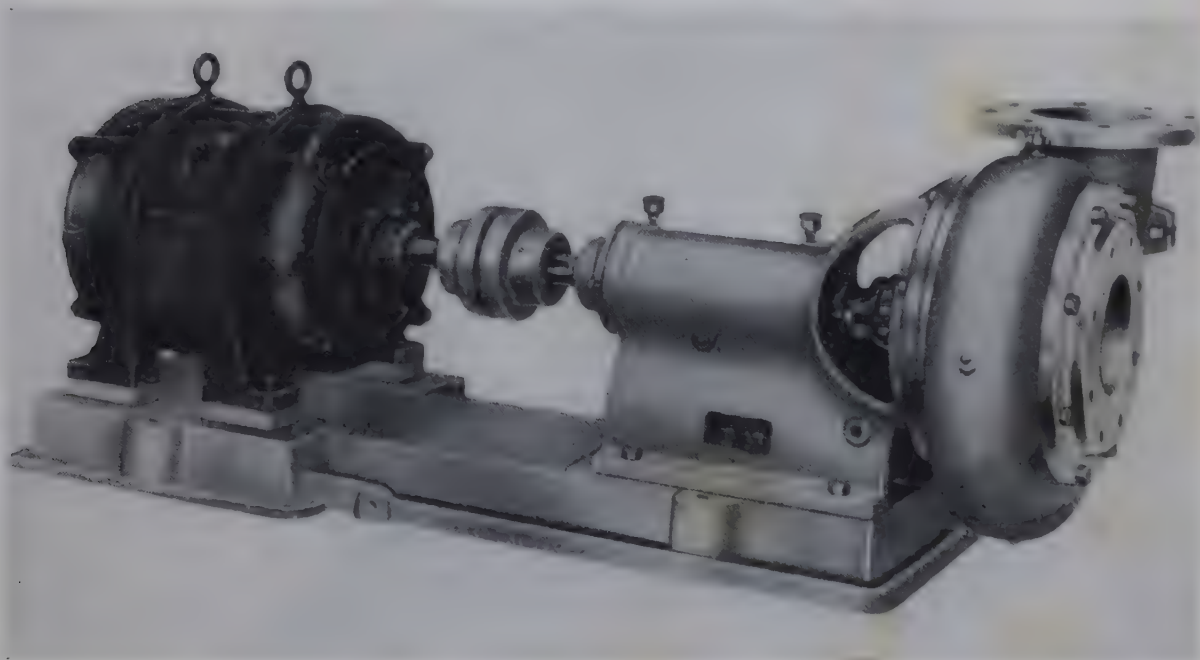
Rotary pumps

Gear pump

Vane pump

Lobe pump

Reciprocating pumps	Piston pump Deep-well pump Lift pump Plunger pump Diaphragm pump
Pumps using air or vapor as an adjunct	Blow case Pulsometer Air Lift
Miscellaneous devices	Axial-flow pumps Aspirator or jet pump



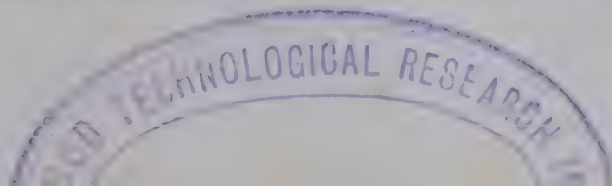
(Aurora Pump Co.)

Figure 12. Centrifugal Pump. Direct driven, single suction, single stage.

Centrifugal Pumps

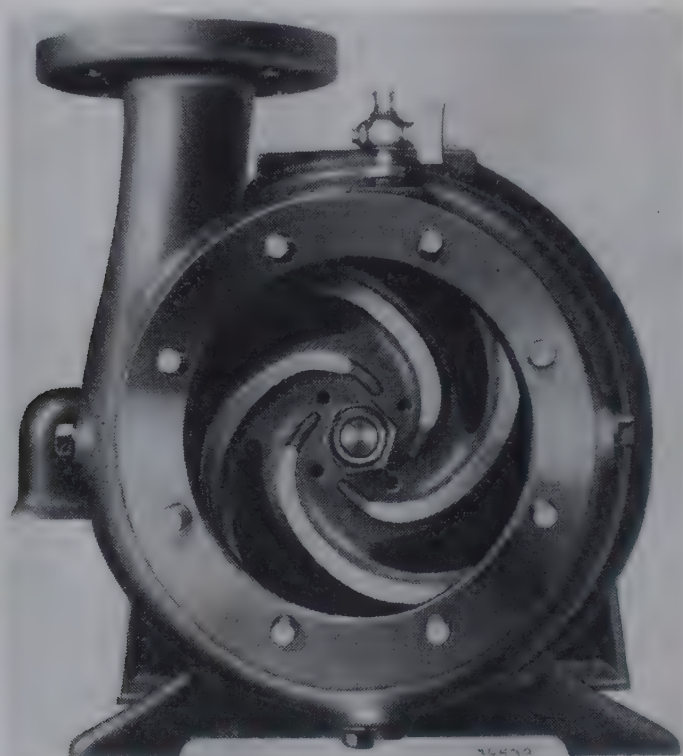
Types. Centrifugal pumps are so widely useful in the chemical industries that, in selecting a pump, it is the general procedure first to ascertain whether or not some style of centrifugal pump will meet the requirements.

The centrifugal pump consists of a rapidly revolving rotor or impeller, shaped so as to impart centrifugal force to a liquid as it passes through the pump; a casing to hold the impeller and liquid; pipe inlet and outlet; stuffing boxes; and the necessary drive mechanism. For a pump which is so basically simple it is amazing that there are so many patterns and variations in style.



Capacities run from 2 to 100,000 gallons per minute, the pressures developed ranging from a few pounds to several thousand pounds per square inch.

Volute Pump. The volute pump is the simplest of the centrifugal pumps. The liquid flows in near the shaft and is discharged tangentially at the tips of the rotor. The name "volute" is descriptive of the shape of the casing.



(Ingersoll-Rand Co.)

Figure 13. Centrifugal Pump with End Plate Removed to Show Impeller.

Diffusion Ring Pump. The diffusion or turbine pump has a so-called "diffusion ring" located between the tips of the impeller and a circular peripheral chamber inside the pump casing. This type of construction is more complicated and expensive, but gives somewhat improved pressure characteristics and is often used in multi-stage high-head patterns.

Factors in Design and Operation. *Impeller.* The impeller is available in more patterns than any other part of the pump. The "standard" impeller is an open spider-work of blades normally curved backward and away from the direction of rotation. The blades may be fastened to a plate to give it greater rigidity, or between two plates to give somewhat improved pressure charac-

teristics. The blades of the impeller are almost straight on some designs, and very carefully tapered and curved on others. The latter design was developed to give such a gentle pumping action that green peas or even sectioned tomatoes, suspended in water, can be passed through these pumps without being crushed.

Stuffing Box. The gland around the rotating shaft is the only point of real wear in the centrifugal pump, and the first point of leakage, especially if the pump is being used to handle liquids containing gritty substances. Glands are sometimes provided which have channels for the admission of streams of clarified liquid pumped into them by small auxiliary pumps. The liquid in these channels keeps them flushed and prevents grit from accumulating. This seal also reduces air leakage which would reduce capacity when the pump is operating with a high suction. Deep stuffing boxes are also advisable for chemical centrifugal pumps. These are particularly necessary if the liquid is corrosive toward the material used for packing.

A new type of centrifugal pump, completely enclosed, has a pump rotor which is actually the rotating element of a motor. The field coils are in the casing of the pumps. This pump has no glands since no rotating part goes through the casing.

Drive. One of the outstanding advantages of the centrifugal pump is that it can be operated efficiently at speeds of 1200 to 3,600 rpm, the range of speeds available in common alternating-current motors. Therefore, most modern centrifugal pumps are direct-connected to electric motors, thus eliminating the need of speed reducers, pulleys, and other auxiliaries. Pumps may also be direct-driven by turbines or by gasoline or diesel engines.

Inlet. The simplest pump inlet is one in which the liquid is introduced in a pipe placed in a line which would be an extension of the drive shaft. However, in pumps of large diameter or high speed, this side inlet is likely to cause some difficulty because of unbalanced axial thrust on the pump shaft. To eliminate this difficulty the double-suction inlet has been introduced. This inlet is really two channels, one leading to each side of the impeller inlet.

Priming. The ordinary centrifugal pump is not self-priming; that is, it must be filled with liquid to start the pumping action.

This is usually done by locating the pump so that its inlet is below the normal level of the liquid. When this is impossible, the use of one of several self-priming styles of pumps is indicated. In one of these, a small volume of liquid is stored in a tank located above the pump casing. By means of automatic valves and floats, this liquid is caused to drain into the pump when it is started; the tank is refilled immediately.

Another self-priming pump holds a small quantity of liquid in a trap on the inlet side. As the pump is started, a froth of liquid is pulled into the impeller and discharged to a separator where the liquid is separated from the air and returned to the inlet. This operation proceeds for a few moments until the main body of liquid can be drawn into the pump.

Pressures Developed by Centrifugal Pumps. A single centrifugal pump, even if operated at high speed, will normally develop pressures considerably less than 100 psi. However, since the pump actually produces a "differential" pressure, if two or more centrifugal pumps are connected in series, each will raise the outlet pressure by an amount equal to the differential head it can develop. By placing the several "stages" in a specially designed common casing, the pressure drop between pumps can be reduced to a minimum, and the several pumps can all be operated from a common shaft. Multi-stage pumps with as many as sixteen stages have been designed and built to develop pressures well over 1,000 psi.

Plans of Operation. A centrifugal pump of standard pattern can be used with the shaft in a vertical position and can be completely submerged in the fluid which is to be pumped. This is the familiar sump pump which is so widely used. The major feature of this pump is the fact that it has no packing gland; hence there is no concern about leakage around the shaft. The motor is usually mounted on top of a heavy plate which forms a support for the motor and pump; this is often used to cover the man-hole through which the pump is lowered into the tank. It has important applications in locations where leakage of toxic substances might be dangerous, where it might be subjected to highly corrosive agents or where chemical solutions attack the packing materials.

If, for some reason, it is not convenient to place the pump

the tank, or if it is desired to have one pump service a series of tanks, the same result, as far as omitting stuffing boxes is concerned, can be obtained by placing the pump in a sump connected with one or several tanks.

A special variety of the sump pump is the multi-stage deep-well pump. In this case both a drive motor and multi-stage pump are constructed in a tube small enough to be threaded into the bottom section of a well casing having a diameter of 4 to 6 inches.

Materials of Construction. Because the centrifugal pump is so simple in design and has no wiping surfaces except at the stuffing box, it can be made of difficult-to-machine materials. Thus, it is available in stainless steel, aluminum, "Monel," "Hastelloy," "Duriron," glass, ceramic, and hard rubber or plastic; or of bronze or steel covered with lead, silver, gold, tin, rubber, plastic, or glass, as well as in the more common metals and alloys such as steel, brass, or bronze. The possibility of securing a pump constructed of a noncorrosive material is highly important to the chemical processor.

General Operating Features. The centrifugal pump has a number of features which make it popular, many of which have already been indicated. A summary is as follows:

a. There are no close tolerances in the pump body. This makes the pump of interest since it can be

1. constructed of any one of a wide variety of corrosion-resistant materials,

2. used to handle liquids containing considerable quantities of sand or grit,

3. constructed with little machining and therefore at reasonably low cost.

b. The pump can be throttled by means of a valve or the discharge can be completely closed without harm to the pump.

c. It can be operated in any position.

d. Pumps having fairly large capacity are reasonably small in size.

e. Pumps travel at about the same rotational speed as is common for electric motors, gasoline or diesel engines, and steam or water turbines. The drive can therefore be simple, direct, and space saving.

f. Pumps are available to deliver a wide range of pressures and quantities.

g. Pumps are simple in construction and operation. Some styles can be dismantled in minutes to allow inspection, and cleaning or sterilization of the interior. This feature is of importance in the food industries.

h. These pumps deliver a liquid flow which is steady and the operation is usually relatively quiet.

The centrifugal pump obviously does not meet every requirement of pumping service. Some of its shortcomings are:

a. It does not easily handle liquids of high viscosity.

b. There is no direct relationship between pump speed and volume of delivery.

c. The ordinary pump is not self-priming, although several self-priming pumps have been manufactured.

d. The pump is essentially a high-volume, medium-head pumping unit. It is

1. not as efficient as some other pumps for very low volumes since it cannot be run slowly to pump small quantities,

2. much heavier and far more expensive than some other pumps for high pressures with medium or low deliveries,

3. not as satisfactory as other pumps for very large volumes at very low heads.

e. It cannot deliver very high pressures (5,000 psi or more) without being excessively complex in design.

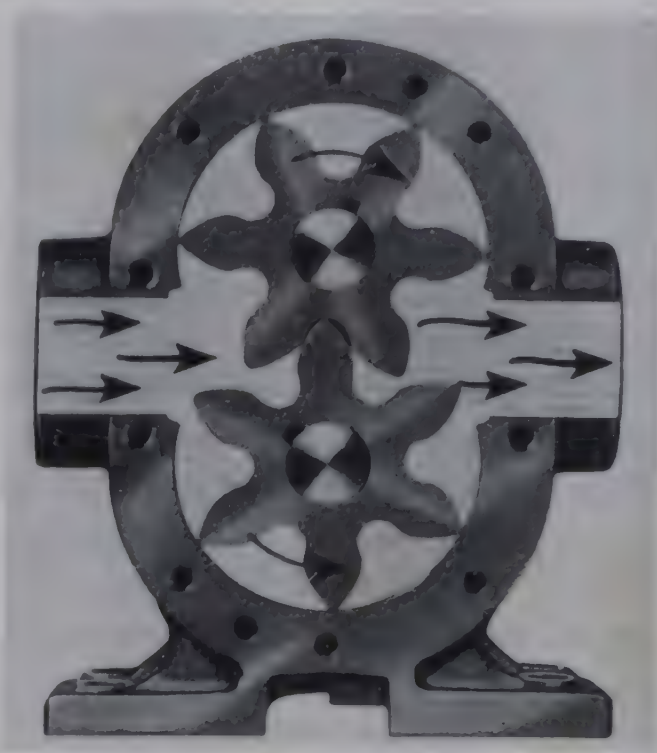
Rotary Pumps

Several different pump designs are included in this group. In the operation of these pumps, liquid from an inlet port is trapped in a compartment which is reduced in size as the shaft turns; the liquid is delivered to the discharge port from the reduced compartment. All of them rotate at relatively slow speeds (100-300 rpm).

The rotary pump finds its greatest use in pumping viscous liquids, in delivering small volumes at high pressures (up to 5,000 psi or more can be obtained in a single stage), and because

of its accurate delivery, for metering liquids into a system. It delivers an almost nonpulsating flow, and is self-priming.

The main defect of this type is that the pump has rather large metal surfaces moving in contact. These are subject to excessive wear unless the liquid is lubricating in character and is completely free of gritty material. The pump has low capacity (although larger rotary pumps are available to handle volumes up to 2,500 gpm); power requirements are somewhat high; and the speed of 100 to 300 rpm requires belt drives or speed reducers if driven by ordinary electric motors. The pump will be overloaded if operated against a closed discharge and requires, therefore, a safety relief valve or circuit breaker.



(Roper Pump Co.)

Figure 14. Rotary Pump. Gear Type.
Schematic drawing to show operation.

Reciprocating Pumps

The fundamental pattern of reciprocating pump is a single direct-acting piston in a cylinder. The liquid is drawn into the cylinder while the piston is moving outward, and is driven out as the direction of motion of the piston is reversed. Valves in the inlet and outlet of the cylinder direct the flow of liquid. Modern pumps are built in several styles which embody numerous improvements introduced to overcome some of the many defects in the basic design.

The pulsating flow of the simplex reciprocating pump is very troublesome. It may be reduced by installing a gas filled pressure bell on the outlet line; many pumps are supplied with such a bell. Duplex and triplex pumps are also used for this purpose.

These are multi-cylinder pumps, the cylinders operating in parallel. The pump strokes operate 180° , 120° , or 90° out of phase, thereby giving a smoother flow than can be obtained with a single-cylinder pump. Many multi-plex pumps are in use, but new installations are rare, since other types of pumps are now available which will give the same results and which are cheaper and more efficient.

The longitudinal thrusts of single-action pumps are unbalanced. Improvement of pump action can be obtained by closing the drive end of the cylinder and making both strokes of the pump deliver liquid. The double-acting pump automatically becomes a duplex design.

The pressure packing on the piston pump is in the form of a ring on the piston. If it becomes worn or fouled, the entire pump must be dismantled for repair. To overcome this difficulty, a pump has been devised in which a smooth solid cylinder slips back and forth inside a packing held in the casing. Thus the packing can be replaced or repaired without excessive effort. This type is called a plunger pump.

A major fault of the ordinary reciprocating pump is its inability to handle successfully liquids containing gritty solids. This difficulty has been virtually eliminated by the use of the diaphragm pump. In this pump, the usual piston is replaced by a flexible diaphragm, which, when flexed by a rod and crank, forces liquid in and out of the pump cylinders. It is single-acting. The heads developed are low, but it is widely used, especially in connection with thickeners and clarifiers.

The reciprocating pump has several operational features which favor its continued use. By use of long pump rods the pump can be operated at a location remote from the power source. The use of this pump at the bottom of deep wells is thus made possible. Further, since it has positive displacement, its use as a metering pump is made possible. The pulsating flow of this pump is one of its undesirable features; the large wiping surfaces which erode rapidly if liquids contain grit is another; and the reasonably slow speed and reciprocating motion, as well as low capacities and somewhat low efficiencies, are others.

Compressed-air Pumps

Several types of pumps use air or vapor (steam) to pump liquids; since all are characterized by the absence of moving parts, there is no necessity for packing glands. These pumps can handle highly corrosive, toxic, or extremely dirty liquids.

Blow Case. The blow case is an industrial counterpart of the ordinary laboratory wash bottle and functions in exactly the same way. The liquid is allowed to drain into the tank until it is nearly full. Then the inlet valve is closed and compressed air is admitted to the tank. The liquid is ejected through a dip tube or through a pipe leading from the bottom of the tank. The valve operation may be carried out manually or automatically. The major disadvantage of the blow case is its intermittent pump action. Because it is extremely simple in construction, it can be made of any material, such as stoneware, glass-lined steel, or other non-corrosive material.

Pulsometer. The pulsometer is a special type of automatic blow case; steam is admitted to a cold chamber until it is filled with a vapor, the steam inlet valve is then closed and the condensing steam creates a vacuum which draws in the liquid. When the container is filled with liquid, the steam valve is again opened; the steam pressure drives out the liquid; then the chamber is refilled with steam, and the cycle is repeated. The pulsometer usually consists of two chambers which alternately fill and discharge the liquid being pumped. The pulsometer will often operate months or years without attention, and for this reason it is often installed in remote locations. It uses large quantities of steam and mixes condensed steam with the liquid being pumped.

Air Lift. The air lift provides a very effective method for the elevation of corrosive liquids. It is better than the blow case, since its pumping action is continuous. Because of its simplicity it needs little attention or inspection. In the air lift, compressed air is introduced near the bottom of a tube or pipe partially filled with liquid. The air mixes with the liquid, and reduces its apparent density. The liquid-air mixture is then forced up the tube by the hydrostatic pressure of the liquid on the outside.

The air lift has several disadvantages. Its effective lift may not be great and it is rather inefficient from the standpoint of power consumption. It is good only for lifting purposes, and the liquid must be run into the open at the top of the lift, or the air vented away from the liquid by other means.



(Ingersoll-Rand Co.)

Figure 15. Axial Flow Pump. Propeller type. Vertical style.

Axial-flow Pumps

In the axial-flow pump, the liquid passes through the pump in the direction parallel to the shaft. Power is applied by means of a propeller or screw impeller. The ordinary axial-flow pump is a low-head, high-volume pump used for elevating large quantities of liquid only a few feet at most. Modern patterns, however, may combine the axial-flow with a semi-centrifugal type impeller to give a combination pump, which, when arranged in stages, can develop somewhat higher pressures.

Jet Pumps

The laboratory aspirator, enlarged to form an industrial-size unit, is a popular type of pump. The aspirator is operated either by high-pressure steam or air or by a high-velocity jet of the liquid being pumped, the liquid jet being produced by a second pump which may be located some distance from the jet pump.

This pump is of considerable interest because of the absence of moving parts within the pump, which makes it adaptable for handling corrosive materials, and because it can easily be inserted in a small diameter pipe. It is quiet in operation and requires no lubrication or adjustment.

Its major disadvantage is that it mixes air, condensed steam, or the pumping liquid with the material being pumped. It is also

an inefficient user of prime steam. If liquid is used in the jet, a pump of mechanical design is required as an auxiliary.

PIPE

A full knowledge of pipe construction, installation, and use is vital in the successful design and operation of a chemical plant.

General observations relating to pipe and pipe systems involve such items as the cleanliness and smoothness of the inside of the pipe (freedom, therefore, from rust, scale, and residues of fabrication and assembly), and the absence of sharp angles, of rough places at fittings, and of pockets in which solids may settle. Pipe should be corrosion-resistant to prevent high maintenance charges and the possibility of contaminating the product. It must often withstand high temperatures or pressures, or both.

Pipe Construction

Rigid steel pipe is available in two general types, depending upon the method of production. The cheapest and most widely used is of seamed construction—nearly always welded.

Seamless pipe, in general, is superior to welded pipe for high-pressure service, and is more expensive to manufacture. The gain in physical properties, however, often more than compensates for the additional cost.

Cast-iron and cast-steel pipe are made by sand-casting or centrifugally casting molten metal. Sand-casting is cheaper but gives a more porous and weaker product.

Much non-ferrous tubing is formed by heating the metal or other substance to incipient fusion and forcing this material through dies which give it the shape of a tube. This tube may be drawn to give a desired standard dimension, or it may be used in the size as it comes from the dies.

Flexible steel tubing consists of a thin steel strip wound in a helix and formed into a tube by a crimped joint. The tubing is useful by itself and it often serves as armor for rubber tubing required to withstand high pressures.

Pipe Sizes

There are a number of methods of designating pipe sizes. Most commonly encountered are the so-called iron pipe sizes which

are applied to most welded pipe up to 12-inch inside diameter, and to various kinds of alloy pipe such as brass, "Monel," aluminum alloys, and others. In this designation the pipe is measured by its *nominal inside diameter* (approximate inside diameter). Extra strong and double extra strong pipe have thicker walls, but the same outside diameter as standard pipe.

Small-diameter pipe is furnished in the following standard sizes (nominal inside diameters): 1/8 in, 1/4 in, 3/8 in, 1/2 in, 3/4 in, 1 in, 1 1/4 in, 1 1/2 in, and 2 in.

Other pipe and tubing are specified by either inside or outside diameter and wall thickness, and some may also include pressure ratings.

Pipe Materials

Pipe is made in literally as many types of materials as can be easily formed into a rigid and strong cylinder, which are cheap enough to be competitive, and resistant enough to the fluids to be transported and to the surroundings in which they are to be placed to give reasonably trouble-free service.

Ferrous Piping. Because of the ease with which it can be worked, its low cost, high strength, and reasonably long life, iron is the favored material for pipe manufacture. Most iron pipe in general use is actually mild steel, and is placed on the market as black pipe. Much of it is galvanized or enameled, which improves its appearance until it is sold, but has little real value after it is placed in service. Very pure iron, known as wrought iron, is considerably superior to mild steel in corrosion resistance. Cast iron gives good resistance to soil corrosion; it is used principally in water distributing systems and in sanitary installations.

Ferrous alloys are very important pipe materials, notably the chrome irons and the various chrome-nickel steels. The chief interest in these materials lies in their high resistance to corrosion. Many of them are also important because they maintain high strength at elevated temperatures.

Non-ferrous Piping. Aluminum and various aluminum alloys are important as pipe materials because of their resistance to certain types of corrosion. Some alloys of aluminum are almost as strong as steel. The main disadvantage of aluminum pipe is

its unusual loss in strength as its temperature is raised. Aluminum pipe is manufactured and sold in ordinary iron pipe sizes, as well as extra-strong and double-extra-strong wall thicknesses. Much aluminum is also made into tubing.

Copper pipe and tubing finds important uses, and several copper alloys, notably brass, bronze, and "Monel" also find wide application. Copper pipe is manufactured in iron pipe sizes, and in a number of tubing sizes. Brass costs less, works easier and is somewhat stronger than copper. Brass also is sold in both regular iron pipe sizes and as tubing.

Bronze, an alloy of copper and tin, is much more corrosion-resistant, has a higher tensile strength and is much more costly than either copper or brass. Both bronze and "Monel" are being replaced in pipe and fittings by stainless steels.

Lead possesses unusual resistance to most acids and for this reason is much used as a pipe material in chemical plants. Its major disadvantages are its low strength and its tendency to creep.

The corrosion resistance of lead and the high tensile strength of steel can be combined by using lead as a lining, homogeneously bonded to the inner surface of a steel pipe. This lead-lined steel pipe is designated by its actual inside diameter and a letter to indicate wall thickness.

Nickel is useful for handling alkalies; block tin is used in piping systems for handling distilled water; and steel pipe lined with metals, such as silver, gold, tantalum, tin, and other materials, is widely used in those cases where such metal linings afford the necessary corrosion resistance, and the steel pipe the required strength.

Nonmetallic Pipe. A wide variety of nonmetallic materials find use either for the fabrication of pipe or tubing, or as linings for steel or other metallic pipe.

Concrete. Concrete pipe is particularly useful for large-diameter pipe lines designed to carry liquids under low pressures. Concrete pipe is made in sections reinforced by steel rods. Steel pipe lined with concrete is stronger than reinforced concrete pipe. "Transite" pipe, made of cement and asbestos fiber, is tough, strong, and more easily worked than concrete. It is

particularly good for handling corrosive materials and for installation in corrosive soils.

Ceramic. Ordinary sand-glazed terra cotta pipe is made and used in large quantities for sanitary piping. Its resistance to corrosion, either by liquids passing through it or by the soil in which it may be placed, and its low cost lead to its extensive use in chemical plants.

Chemical stoneware is made of clay which has been deaerated. It is made with thin walls as well as thick, and thus it can be used for the construction of coils which are satisfactory for mild heating or cooling service, as well as for the transport of fluids.

Porcelain pipe is also being received with increasing favor. In spite of its high cost, its great resistance to corrosion and reasonably good resistance to thermal shock have made it a favored material for many installations.

Glass. Glass is used in the manufacture of all-glass pipe, or as a glaze or lining on the inside of steel pipe. Many different kinds of glasses are available, but "Pyrex," with its high resistance to thermal shock, is used in most installations. All-glass pipe is of particular interest because of its transparency—the only kind of pipe possessing this property. Glass linings in steel are very satisfactory; the steel shell reduces the hazard of mechanical failure.

Rubber. Rubber tubing is a common laboratory item, and rubber hose, such as garden hose and air hose, is widely used. Industrial hose made of rubber is prized for the same properties as its domestic or laboratory counterpart—its flexibility and inert nature. Industrial rubber hose is built with either fabric or metal reinforcement, or both. Rubber may also be used as a lining in steel, to which it can be very tightly bonded. So-called "hard rubber" is also made into a rigid pipe.

Plastic. A number of plastics are regularly made into industrial pipe or tubing, or are used for lining in metal pipe. Neoprene and "Thiokol," made into flexible hose resembling ordinary rubber hose, are used for handling petroleum and other materials which attack rubber. Saran is a plastic having high chemical stability. It is somewhat flexible, and is also partially transparent. Bakelite and other phenol-formaldehyde resins are used for making pipe resembling hard rubber, or are used as linings in metal pipe.

Several plastics are now available as paints which can be applied by the user of metal pipe to give fairly good linings or coatings.

Wood. Where iron contamination is to be avoided, and where pipe is to carry water and remain filled most of the time, wood pipe is quite satisfactory. Wood is used in two ways. Pipe is fabricated of redwood or cypress staves bound with steel rods; or the wood serves as a lining in steel pipe.

Carbon. For unusual demands pipe made of other materials is available. Carbon pipe, for example, is used under certain circumstances when its corrosion resistance is necessary.

Pipe Joints and Fittings

Pipe fittings have a number of functions to perform. They are used to: (1) join lengths of pipe, (2) provide for a change of direction, (3) provide for a change of diameter, (4) permit the addition of a side connection, (5) close the end of a section of pipe, (6) allow for dimensional changes in the piping system due to thermal expansion and contraction, (7) permit radial freedom of movement and accommodate misalignment in the piping system, or (8) provide various combinations of the above. They are also used to join pipe to tanks, pumps or other equipment.

Screwed Joints and Fittings. Screwed fittings are manufactured in a wide variety of standard styles, sizes, and pressure ratings. Fittings available for joining lengths of pipe or for extending the length of a line are those such as the coupling, nipple (close, short or long), and union. The ell (90° and 45°), street ell (90° and 45°), return bend, and others give a means for changing pipe direction. The reducing coupling or any of several bushings can be used to change pipe diameter. The cap and plug will both close a pipe, and the tee, wye, and cross are means of adding side connections. Various combinations are also available.

Screwed fittings are available in sizes up to 24 in, but are rarely used in sizes above 4 in because of the difficulty of pulling a joint tight with ordinary tools. Sizes of screwed fittings are specified by noting the larger size first, e.g. 1 in by $3/4$ in reducing coupling.

The tee is designated by the size of the "run" and the size of the side outlet in that order.

In order to obtain a leakproof joint it is usually necessary to place a luting material on the threads of the joint before it is assembled. Materials such as litharge and glycerine, white lead in oil, and several proprietary mixtures are satisfactory for this purpose.

The Bell-and-spigot Joint. The bell-and-spigot joint is cast integrally with the pipe or fitting. It is used extensively for cast iron and ceramic pipe, although both may be made with ends for other types of joint.

In the common type of joint, the closure is completed by pouring lead into the joint and calking it, or by filling the joint with special cements such as molten sulfur.

In special types of this joint following rings and other devices are used to improve the efficiency and the permanence of the connection.

Flanged Joints. Flanges have long been used for joining pipe. They are of particular interest because of the relative ease which they may be assembled and disassembled. They are nearly always used in assembling large pipe if the pipe must be taken apart at regular intervals for cleaning or repair. Flanges may cause some difficulty in erecting a piping system because of the necessity of aligning the bolt holes in the companion flanges. Flanged fittings, such as tees, ells, and reducers, are used to fabricate all flanged piping systems.

Flanges are furnished with a number of different facings. Most used is the common flat face. This flange cannot be pulled tight enough to hold a high pressure and most of the improved designs differ from the flat face pattern by the means provided to allow higher pressure on the facing and to prevent the gasket from blowing out. Raised face flanges, grooved facings, male and female facings, are all available.

Although some kinds of pipe, such as cast iron or cast steel, may have the flange cast as an integral part of the pipe, most flanges are made separately and attached to the pipe as the pipe line is fabricated. A method often used is to screw the flange on the pipe. However, the prevalent method of attaching flanges is by

welding. The flange may be a slip-on style, welded at the back or face or both; or it may be a forged welding-neck flange butt-welded to the end of the pipe. Flanges may also be attached by rolling the pipe into the flange with a special pipe expander.

The flange face sometimes is made smooth enough so that no gasket is required. The ordinary method, however, is to give the facing a machine finish and to place a soft gasket between the faces to take up the slight irregularities. These gaskets may be made of such nonmetallic materials as rubber, asbestos, or vulcanized fiber; or they may be made of lead, copper, soft steel, pure iron, "Monel," brass, or other metals. The gasket material must be able to withstand rather severe service requirements: for example, it must be soft enough to make a tight fit, it should not creep at either low or high temperature, it must not melt out of the joint, nor soften enough to blow out, and in many cases, it must be resistant to corrosion.

Sweat Fittings. An important method for joining easily solderable tubing such as copper or brass is the use of the sweat fitting. When properly made, the joint is firm, easy to assemble and disassemble, and gives a smooth interior to the tubing at the joint. The fitting is applied by slipping it on the tubing, heating the joint with a blow torch, and then applying solder to a small hole in the side of the fitting. The solder flows into the space between the tube and fitting by capillary action.

Compression Fittings. The compression fitting provides a method for joining small soft copper or brass tubing. The fittings are in two parts. The tubing is slipped through a loose nut, flared to a cone shape by a special tool, and the flared end pressed against the coupling by the nut.

Welded Joints. The use of arc or gas welding for joining steel pipe is becoming very popular. This method of making pipe joints creates some problems, especially when pipe must be opened for inspection; but normally the welded joint gives better service than any other joint in steel pipe. The ends of the two pipes to be joined are chamfered (beveled), placed end to end, and the V-shaped groove made by the beveling is filled with the weld.

It is common practice to make elbows, tees, and other fittings

by merely cutting the pipe in the proper curves or angles and joining the cut ends. Special welding fittings such as tees, elbows and reducers are available and are in common use. These expedite welding operations and give more rounded contours at the fittings.

Special Joints. Many other highly specialized methods are available for joining pipe and adding fittings to a piping system. For the most part these are custom types of joint, made and used for special materials of construction. Glass, for example, is joined by split flanges tightened against an asbestos insert. "Haveg" uses a split collar which seats in a groove in the pipe wall. Porcelain pipe is often joined by friction collars which hold against roughened areas near the ends of the pipe section. Rubber hose is often attached to fittings by slipping the hose over a corrugated nipple and attaching clamps.

Special Fittings. The fittings described in preceding sections are all used for making rigid connections. In addition to these there are fittings which are designed to allow linear expansion and contraction in a pipe system with a change in temperature, and those having the function of allowing radial movement of the two sections of a pipe system. The first are called expansion joints; the second, flexible joints.

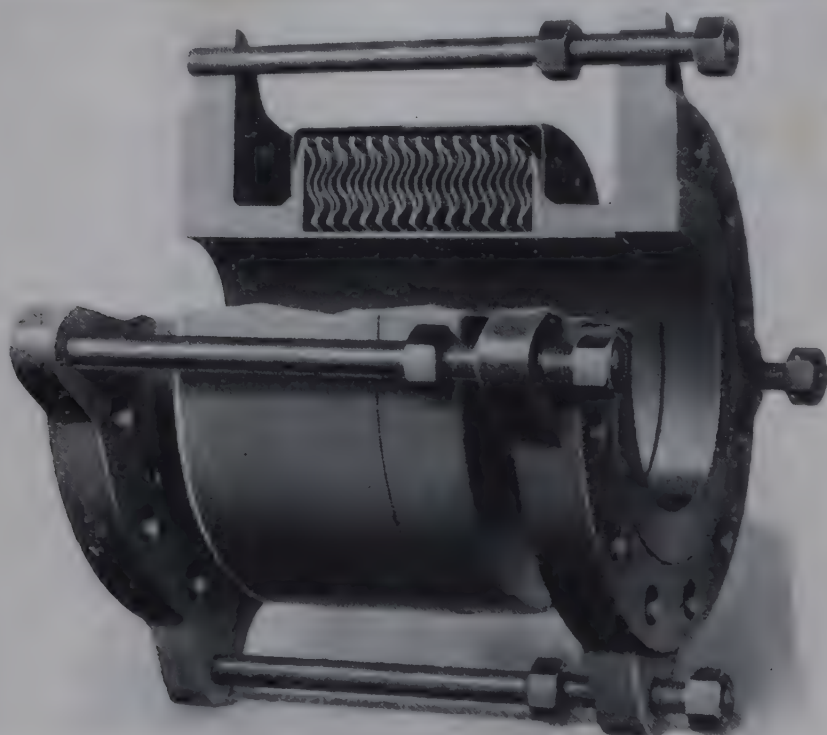
Expansion Joints. Virtually all pipe is subjected to changes in temperature, and if the pipe is rigidly installed without allowances being made for its thermal expansion, serious difficulties will develop immediately. Several styles of pipe fittings have been designed to absorb these changes in length.

Elbows or other fittings providing a change in direction often allow enough flexibility in a piping system so that special expansion joints are not necessary. It is poor practice, however, to omit a regular expansion joint in any considerable length of straight pipe, regardless of whether or not it ends in elbows, for the flexing produced may be enough to seriously strain the pipe beyond or at the fitting.

The ordinary leaded bell-and-spigot joint allows some expansion and contraction, without breaking the joints, and the high-pressure bells, such as the Anthony and the McWayne Glan-tite joint, permit considerable movement of the pipe. These are, there-

fore, capable of giving enough freedom of movement to accommodate all normal expansion of the pipe.

Dresser couplings, which are made in styles for both small and large pipe, are simply stuffing boxes through which the ends of the pipe are inserted. A guide ring or lugs center the coupling over



(Croll-Reynolds Engineering Co.)

Figure 16. Expansion Joint. Bellows type.

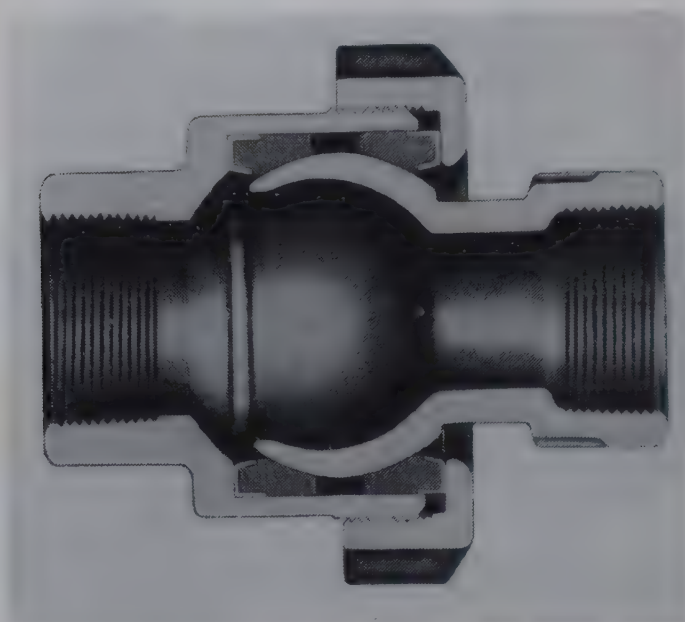
the ends of the pipe and prevent the coupling from slipping off the joint as the pipe works back and forth in it. A packed sliding-sleeve coupling is another type of fitting similar in principle to the Dresser coupling.

A section of corrugated pipe, or a bellows, may be used to take up the motion of the pipe. The latter allows much more expansion, and both permit some misalignment of the pipe leading to the fitting. Since both the corrugated section and the bellows are usually made of material somewhat lighter than the pipe, either coupling is likely to be supplied with a protective sleeve over the outside to prevent mechanical failure of the expansion section.

A plate expansion joint is available for large low-pressure lines. In this joint the pipe leading to each side of the coupling

is attached to the face of large drum-like steel enclosures. The expansion is accommodated by the flexing of these disks which are attached to one another along their rims. An extension of one pipe projecting inside the end of the opposite pipe prevents twisting of the plates.

Pipe bends are mostly used for long high-pressure lines. These are merely U- or Omega-shaped bends which are made of pipe of a strength and thickness equal to the line itself and are inserted



(Barco Manufacturing Co.)

Figure 17. Flexible Ball Joint.

into the line by means of whatever fittings (screwed, flanged, or welded) are used for the remainder of the line. For a large pipe line, these bends may have a radius as great as 30 feet.

Flexible Joints. It is frequently necessary to lead steam, water, or liquid or gaseous chemical material into a rotating unit, or to convey material from a stationary piping system to a moving pipe placed at an angle to the stationary one. One of the simpler ways to do this is to lead the pipe through an ordinary stuffing box. If the pipe is carefully machined on the outside such an arrangement may be quite satisfactory.

One of the several flexible joints is usually more suitable, however, and is likely to give much less trouble from leakage. One of these is the ball-knuckle held firmly against a seat by means of a following flange. This joint allows some knuckle

movement as well as the swivel action. Other patterns using flat wiping surfaces are also available.

It is sometimes necessary to feed material into apparatus having a rocking motion. The several flexible joints so far described are all suitable for this purpose. It is also frequently possible to use flexible pressure tubing where the rocking is confined to a small angle. In the latter case, the inlet must be located so that the tubing is flexed rather than twisted, as it would be if it were attached in line with the axis of movement.

Pipe Installation. Most piping carrying chemicals should be placed above ground. When leaks occur in buried pipes, particularly if they convey dangerous, toxic, or obnoxious materials, they are difficult to find and repair. Moreover, the cost of protective covering for pipe placed underground will normally be greater than the total cost of concrete or steel pipe supports for above-ground piping.

Piping is most convenient to maintain in vertical banks located two to six feet above ground level. If there is some danger of one pipe leaking on others below it and causing trouble by so doing, horizontal banking of the pipes is indicated. Pipe should always be located far enough apart in banks so that wrenches can be placed over any pipe without interfering with the pipe on either side of it.

Where pipe located at waist height above ground interferes with traffic, placement at elevations of from eight to fourteen feet above ground is entirely feasible. The lower elevation will clear pedestrian traffic; the higher will clear truck or rail traffic. Waist-high piping can be conducted over roadways by carrying it up and over bridges of sufficient height. The U-bend thus obtained will often eliminate the need of special bends to meet expansion requirements.

All pipe should be placed in hangers which allow some movement of the pipe. It is seldom good practice to fasten pipe rigidly to the structural elements of a building. A number of suspension hangers, clamps, and other pipe supports have been devised for holding the pipe in an installation and yet allowing it freedom of movement. These range from simple beam clamps and grooved rollers to quite complicated lever and spring sup-

ports to permit large movement without distortion of the pipe system.

Safety Precautions

Safety Devices. In order to prevent material from backing up in a line, or developing pressures too large for the line to handle safely, a number of safety devices have been produced. Nearly all safety devices for regulating pressure in piping systems are based on the principle that it is good practice to place a rupture point at some clearly defined location where materials can be vented to the atmosphere or led to the sewer in the event pressure becomes excessive.

For lines which must be frequently vented, the safety pop-off valve is favored. This valve relieves the pressure at a pre-set level and then automatically closes. The check valve prevents back flow in a line if the outlet pressure builds up to a higher level than the inlet pressure. Both pop valves and check valves are described in a following section.

Safety diaphragms are often installed in pipe lines as protective devices. These are light metal disks having a rupture strength below the safe working pressure of the pipe. They will break if their pressure rating is exceeded and thus relieve excessive pressure in the system. Safety traps are often used for small pressure differences. Dip tubes fall into this group.

Color Code for Piping Systems. Color coding of pipe is a measure designed to improve safety in a plant. According to standards set up by the American Standards Association the following colors are used to designate pipe handling the materials indicated:

Red: fire protection materials

Yellow or orange: dangerous materials

Green: safe materials

Blue: protective materials

Purple: extra-valuable materials

Various combinations and bandings have been devised by many individual plants to extend the above list. One of the first

things an engineer should do upon starting to work in a new plant is to familiarize himself with the pipe identification code of the plant.

In addition to colors, many plants also identify pipe by tags or stenciled signs indicating both the material being carried by the pipe and the direction of flow.

VALVES

The demands of the chemical industry as they pertain to valves include requirements for such operational features as the ability to handle highly corrosive liquids, to operate satisfactorily over a wide range of temperatures, to hold all pressures equally well, and to handle liquids, gases, vapors, and even solids in suspension, through the same valve. These demands compound the problems of valve design.

Valve Construction

Often the peculiarities of the material being handled or the service required limit the material from which the valve can be made, and these, in turn, dictate valve design. Many materials which are adequately resistant to corrosion are difficult to machine, and can be successfully worked only by casting and grinding. Threads and screws must be avoided if possible. Such valves are expensive, and must be made simple in design to keep their cost within reasonable limits. Since much of the cost of the valve is in the machining rather than in the material, valves tend, in general, to be made of somewhat more expensive material than is used in pipe.

The various valves have a number of features in common. Each valve has a handle or handwheel for its operation; a stem to transmit the motion of the handwheel to the closure; a closure, which may be a gate, plug, or disk; and the seat in or on which this device rests. The valve is encased in a body shaped to fit the valve closure. Since the closure must be inserted into the body, there has to be a fairly large opening in it. This opening is covered by a bonnet, which in turn carries the packing gland through which the stem rises and turns.

Valve Classification

The type of valve closure is the most important element in identifying the different valves. Virtually all valves have one of the following three types of closure.

(1) A sliding or rotating member is moved across the flow passage to close it.

(2) A plug or disk of some kind is pushed into or against an opening within the valve body to stop the flow.

(3) The liquid flow is cut off by depressing a flexible diaphragm encased in the valve body, or the side of a tube through which the liquid is flowing.

The more important industrial valves of the first type are the gate valves and plug valves or cocks; of the second, the many styles of globe valve; and of the third, the pinch and some types of diaphragm valve.

Features of Valve Design

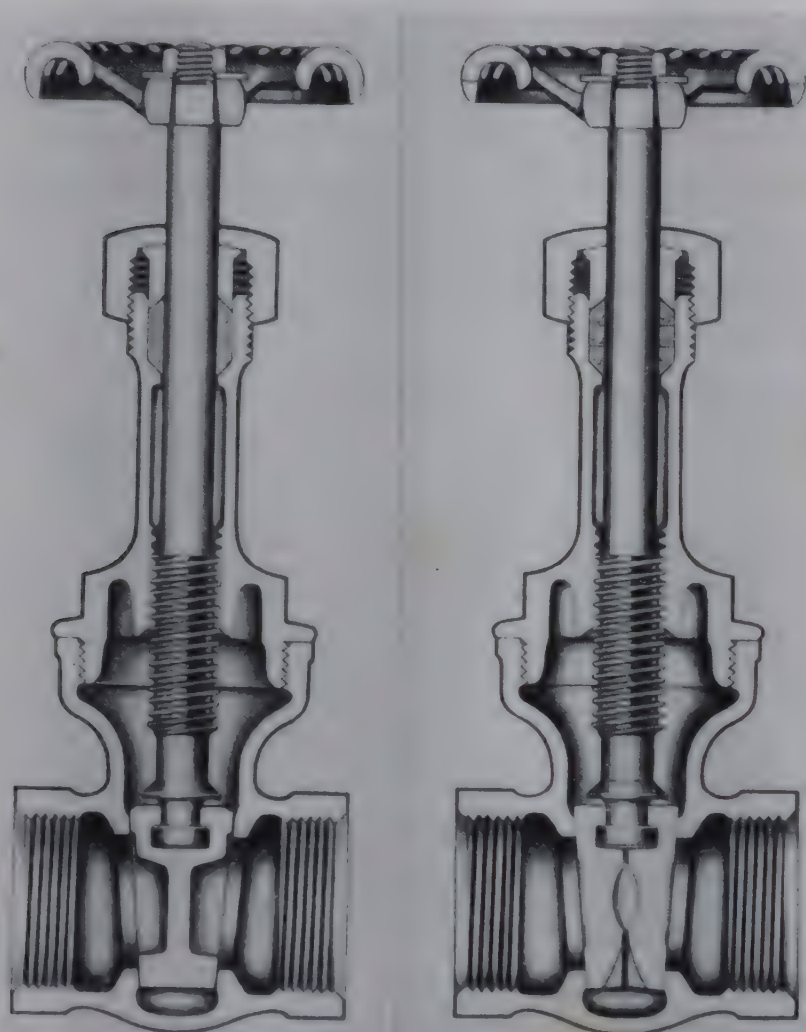
Closure. Gate Valve. The gate valve is usually applicable when the pressure drop through the valve must be small and when the function of the valve is to stop the flow of liquid rather than to regulate it. It is most appropriate for those installations in which the valve remains open most of the time it is in use.

The gate valve is closed by a metallic wedge, gate, or disk which is forced into a tapered seat to form a seal. Slots in the valve body on each side of the seat serve to guide the gate to keep it from turning or tipping, and to make certain that it seats in the proper position each time the valve is closed.

In the gate valve there is a metal-to-metal seal between the gate and the seat. If the liquid is somewhat sticky or corrosive, or if the upstream side of the valve is under considerably greater pressure than the downstream side, the valve is likely to stick badly. This situation has given rise to two variations in the design of this valve.

One type of valve has been designed which has channels in the space between the gate and the seat. A lubricant can be forced

into these channels to facilitate operation. Obviously the lubricant enters the fluid stream; therefore, this type of valve cannot be used where the presence of oil in the fluid stream would be objectionable.



(Crane Co.)

Figure 18. Gate Valves. Sections showing solid wedge gate and double wedge gate.

A much more satisfactory solution to this problem has been the replacement of the solid gate by a leaf type or split wedge gate. This kind of gate is composed of two disks which are lowered into the opening and then forced apart to form a seal against the seat. Opening is the reverse of closing: the toggle or whatever mechanism is used to force the disks outward is first released, and the gate is then lifted out of the channel.

The gate valve, since it is not necessarily held closed by the pressure applied on the stem, is able to accommodate a quick-

opening mechanism. In the quick-opening valve the wheel and threaded stem of the ordinary valve mechanism is replaced by a lever to raise and lower the stem. The gate may be lifted straight out in the conventional manner, or may be rolled in and out of position, pivoted on a pin located in the side of the valve body.

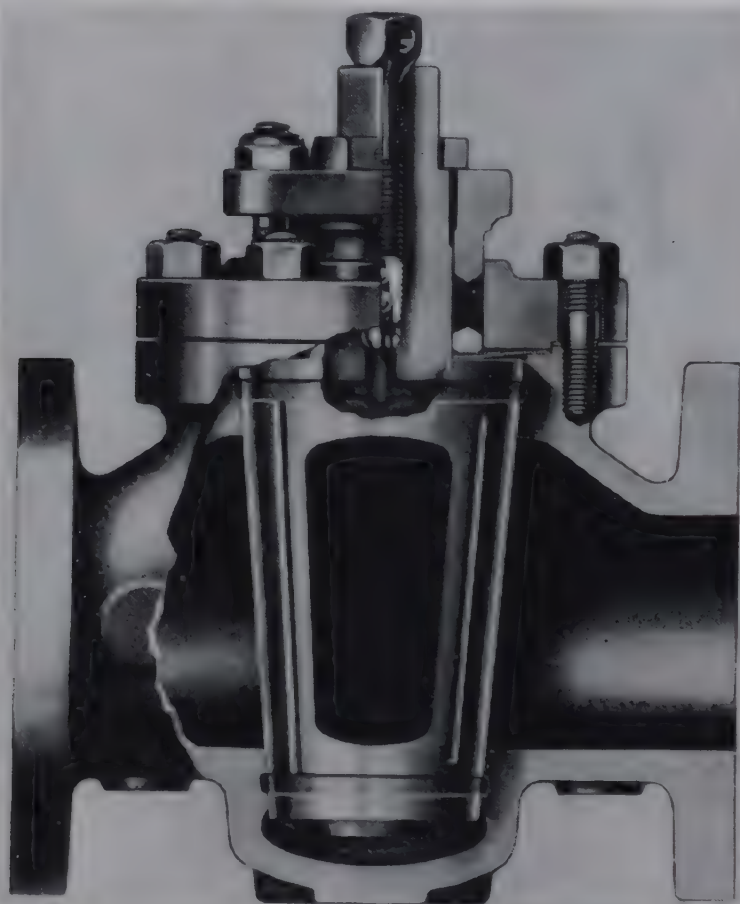
This valve is mostly used where the lines are wide open a good share of the time. If the liquid contains any solids which might settle, these will collect in the irregular obstructions within the valve. The groove at the bottom of the seat becomes filled and the valve cannot be closed. Therefore, if the valve is carrying a liquid containing suspended solids, it will operate properly only if the stem is horizontal. Another disadvantage is that a circular disk moves across a circular opening and the amount of movement is, therefore, not proportional to the size of the opening and thus to the flow through the valve. The gate valve is also somewhat difficult to maintain because of the tapered seat; moreover, the wear on gate or seat as the gate slides into or out of position is high and requires the use of hard materials for gate facings.

Nevertheless, the gate valve does possess the advantage of little obstruction to flow when the valve is open; thus this advantage may be more than enough to compensate for some of the difficulties encountered in its use, particularly in the large sizes where the liquid flow rates are high.

Plug Valve. The plug valve, in its simplest form, is identical in pattern with the laboratory glass stop cock. The only changes required to make the valve suitable for industrial use is to enlarge the valve, make it of metal instead of glass, and add certain operating elements which will make the closure more positive, aid in turning the valve, and relieve it from sticking. The rotating plug may be tapered with the larger end toward the stem (the normal pattern), or the taper may be inverted. It may have a rectangular or circular opening; it may or may not have grease channels for lubrication; and it may be supplied with a means for raising the valve slightly in its seat to make opening or closing easier. Multi-port and multi-way designs are common.

The major advantages of the plug cock are: its ability to be opened or closed with a 90° movement of a handle; the clear indication, by the position of the handle, whether the valve is

open or closed or how wide open the valve may be at some intermediate position; and the possibility of the multi-port, multi-way designs. Moreover, this valve can handle liquids containing solids without clogging or interference with its operation. The valve is satisfactory for throttling the flow of liquids; with



(Walworth Co.)

Figure 19. Plug Valve (Cock).

proper design the pressure drop through the open valve is small. The valve is simple, and maintenance is reasonably easy.

Its most serious defect is evidenced when it is used with corrosive and nonlubricating liquids. In this service the valve is almost certain to stick, even when operated frequently. When operated infrequently it may become so badly frozen in position that its normal operation becomes impossible. This tendency to stick can be reduced somewhat by increasing the angle of taper of the plug and seat or reducing the pressure forcing down the plug. If this is done, its second defect, that of its tendency to leak, is disproportionately increased. Most of the work which has been

done on the improvement of the design of this valve has been directed toward the solution of these two problems.

The problem of sticking has been partially solved by two innovations. One of these is to provide grease channels on the face of the plug to lubricate the valve. This will also aid in keeping the valve from leaking. The use of grease on the valve is limited to those valves used in a service where oil or grease contamination of the fluid flowing through them will be of no consequence. The second approach is to provide hydraulic pressure or mechanical means for lifting the plug slightly in its seat before it is turned. Hydraulic pressure is applied through oil or grease channels leading into the space under the plug. Mechanical lifting is provided by means of tapered collars or other similar devices.

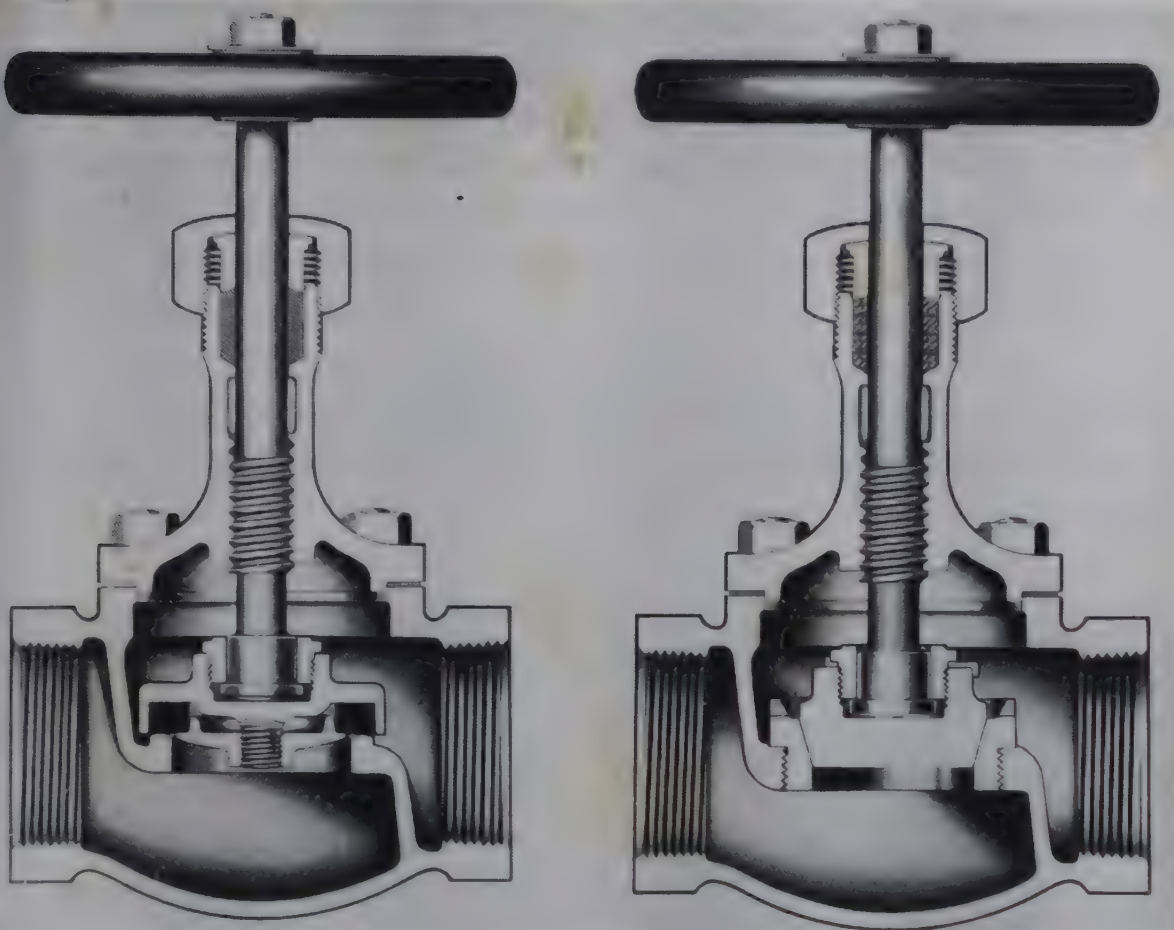
Globe Valve. The globe valve is widely used, not so much in its basic pattern as in one or another of the many variations in style in which it is available. This valve is produced in a multitude of patterns.

The globe valve consists essentially of a plate, disk, or plug which is pushed against an opening and held in the closed position by mechanical pressure. Globe valves are manufactured in many styles, some of which are important enough to be described in some detail.

1. *Common globe valve.* This valve consists of a circular metal seat held rigidly and horizontally in the body of the valve. The closure is pressed against this seat. The seat is normally made of metal and the disk made of the same or other (usually softer) metal. The disk may also hold a ring gasket of plastic, rubber, or fabric.

2. *Angle valve.* The major disadvantage of the common globe valve is that since the fluid changes directions four times within the valve, turbulence is high and pressure drop is excessive. If the valve can be installed in a place where the pipe line passes through a 90° turn, the closure can be arranged to cover, in effect, an extension of the pipe leading into the valve, thus reducing the effect of the pattern on the pressure drop. The angle valve is constructed according to this design.

3. *"Y" valve.* The Y-valve which has the seat in a slanting



(Crane Co.)

Figure 20. Globe Valves. Sections showing disk and plug closures.

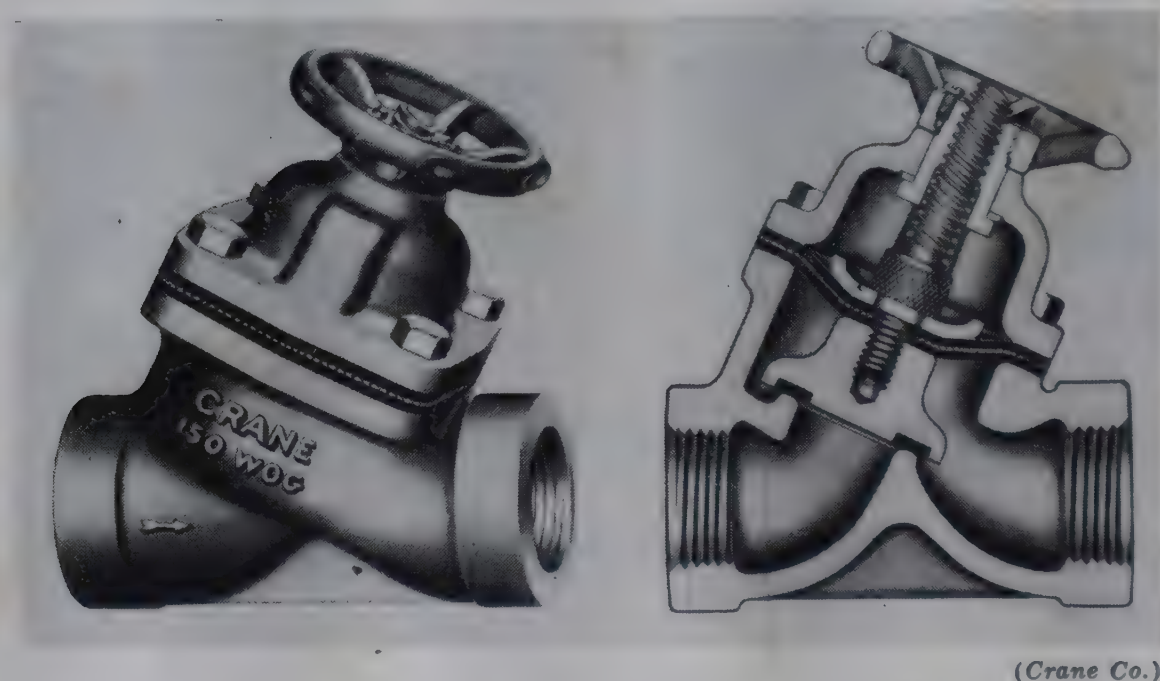
position offers less frictional resistance than the common globe valve.

4. *Tapered-plug globe valve.* A tighter closure can be obtained by inserting a stopper-shaped plug in a tapered seat than by pressing a flat disk over a flat circular seat. This is the principle of the tapered-plug globe valve. Since a sliding fit is obtained in this valve, the need of using a relatively pliable or soft material for the closure is eliminated. Throttling is improved and the valve can be made more resistant to leakage.

5. *Needle valve.* If the principle of the tapered plug globe valve described above is carried to an extreme with a long highly tapered plug, and a similarly formed seat, the needle valve is obtained. This valve is widely used for throttling, and when made of high-strength steels is used for holding exceedingly high pressures.

6. *Diaphragm valve.* One of the features of many of the

styles of the globe valve is that the disk or plug is circular. This can be made piston-like in shape, and can be drawn into a cylinder in the bonnet, thus giving the working parts of the valve some protection against the flowing liquid. Complete protection of these parts can be obtained by use of the diaphragm valve, in which the closure is made by pressing a soft rubber diaphragm down against the valve seat, or in which the valve stem, threads, packing glands, etc., are isolated from the fluid stream by a diaphragm. The valve body and seat can be made of one of the difficult-to-machine but corrosion-resistant materials.



(Crane Co.)

Figure 21. Diaphragm Valve.

The globe valve in its many patterns is a most versatile device and as a consequence its use is widespread. The standard pattern, because of its resistance to fluid flow, is generally used for mostly closed service or in installations where pressure drop is not a factor to be considered. A disadvantage is that the valve is designed for one-way service, a limitation not affecting either the gate valve or the plug cock. This is not often serious, but may sometimes eliminate the valve for some particular installation. The globe valve, particularly in the larger sizes, is not often satisfactory for holding very high pressures. An exception is the

needle valve, but this is commonly available only in the smaller sizes.

Pinch Valves. The pinch valve has its laboratory counterpart in the ordinary clamp used on rubber tubing. It has some modifications, but at least one style of the larger valve operates upon exactly the same principle. Pinch valves are produced in at

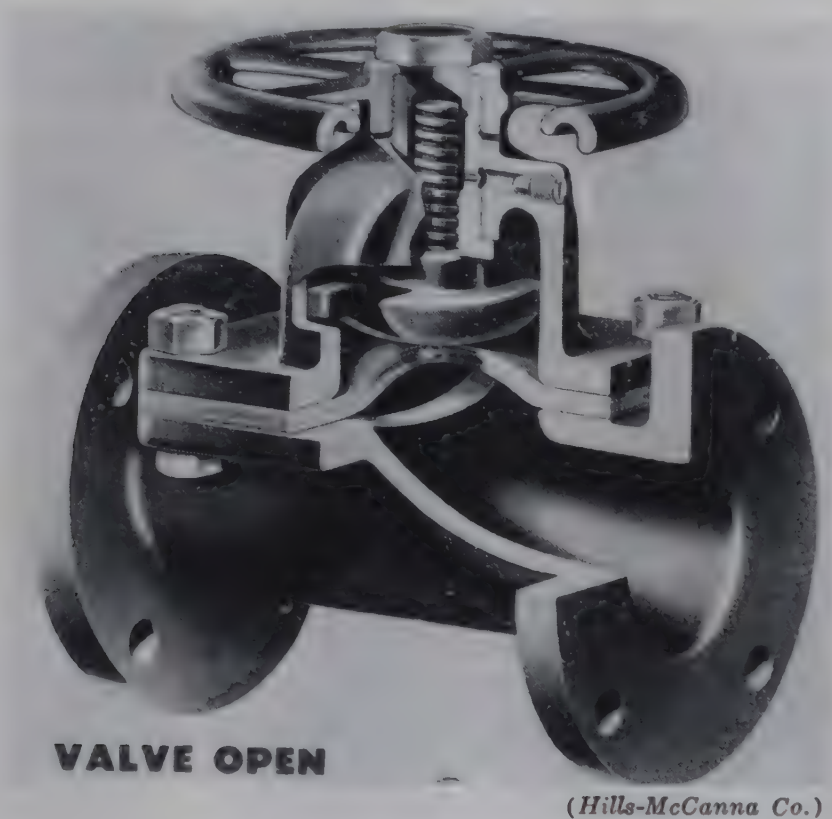


Figure 22. Diaphragm Valve. Pinch closure.

least two general patterns. One of these has a body of rubber or other flexible tubing which is closed by driving the walls together. The other type of pinch valve is somewhat similar to the diaphragm type of globe valve; a crescent-shaped dam in the valve body is closed by pressing a rubber diaphragm against it with a properly shaped wedge.

Other Valves. There are a few other valves in limited use for the control of fluid flow. One of these valves is the Yarway, an industrial adaptation of the sliding plunger valve once commonly used on steam engines. In this valve the movable part is a piston which, as it is moved from one position to another within the cylinder, either shuts off outlet ports located in the wall of the

cylinder or can be stopped in such a position that holes or slots in the piston engage these holes in the wall and permit passage of liquid.

The butterfly valve is another valve occasionally used for controlling liquid flow. Its advantage of closure with a quarter turn of a handle is an important feature otherwise available only in the plug cock. It will nearly always leak, even at very low pressures. Its use is thus rather limited

Bodies and Bonnets. The body surrounding the valve has three functions: (1) to contain the valve seat and closure; (2) to permit the working parts of the valve to be withdrawn; and (3) to hold fittings to permit the valve to be installed. The general shape of the body is dictated by the shape of the closure and seat. The body of the gate valve is slender and tall, that of the globe valve is bulbous, and that of the plug cock is almost cylindrical in shape.

The bonnet, particularly in the way it is attached to the body, exhibits many variations. The smaller brass valves ordinarily have the bonnet screwed to the body or held in place by a threaded following ring (union). Larger size brass valves and many of the iron valves have the bonnet either bolted to a companion flange on the body or are held to the body by U-shaped clips which pass completely around the body of the valve.

Valve Operation

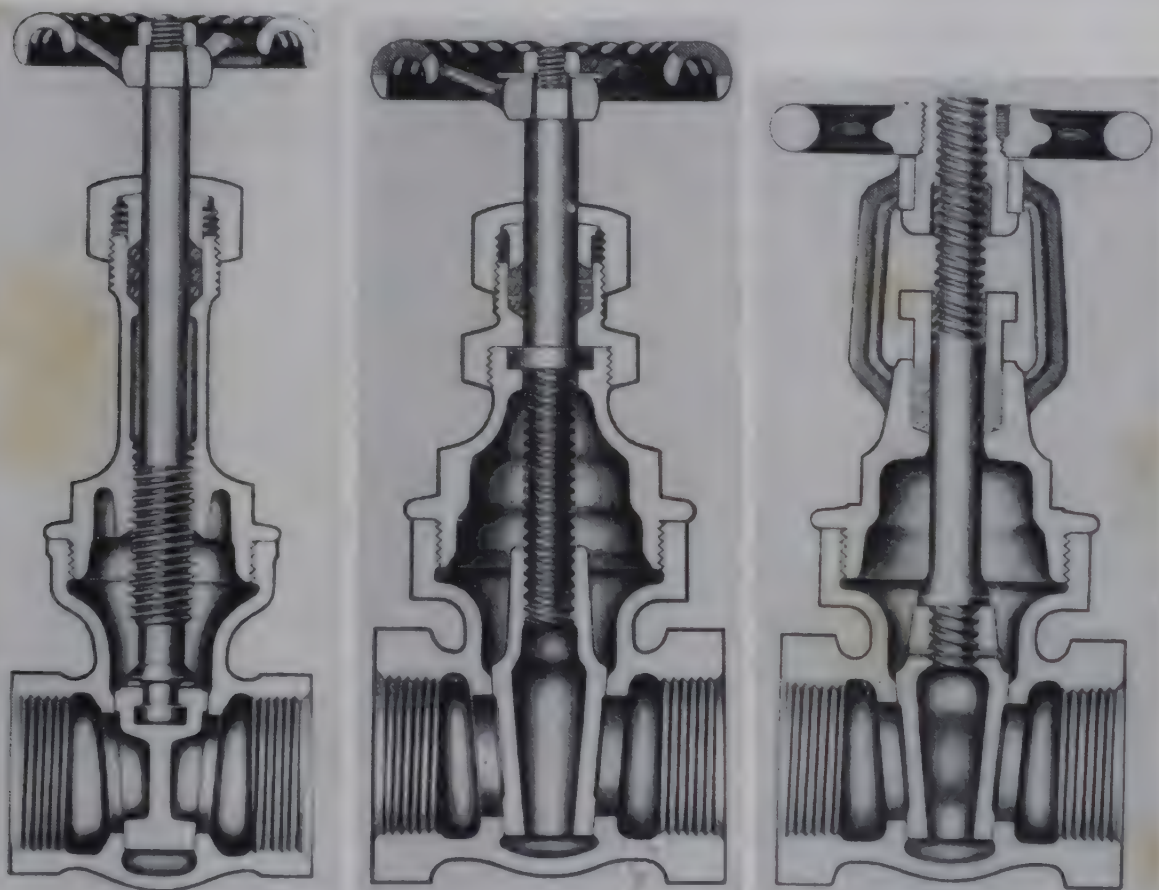
Manual Operation

Most small valves and many large ones are manually operated, manual operation being completely adequate in many situations. In any chemical plant, valves often are installed by the thousand, so that the expense of operating devices may be excessive. Further, many valves are operated at very infrequent intervals.

The type of mechanical device which can be used for valve operation depends on the valve itself. In the gate, the globe, and pinch patterns, the closing device is lifted out of the stream or off the seat to open the valve. Both pinch and globe valves require positive pressure to be applied while the valve is closed. The gate valve does not require this continuous pressure application. The

plug cock and butterfly valve are opened or closed by turning the closure on an axis. Mechanical operation of the valve mechanism takes into account all these requirements.

Threaded Stem Lifting Devices. The threaded stem and handwheel is the normal method of manually lifting a valve closure. This affords positive pressure at all times, and multiplies



(Crane Co.)

Figure 23. Handwheel Operation of Valves. Ordinary (turning, rising stem), non-rising stem, and outside screw and yoke patterns.

the force applied to the handwheel. There are also lever type mechanisms for lifting a valve closure.

1. *Inside screw, Rising stem.* The most common method of valve stem construction is to thread the valve stem in such a place that it engages threads in the bonnet inside the packing gland of the valve. If the liquid is corrosive, or if it carries grit, the open threads in the valve will nearly always give trouble.

2. *Non-rising stem.* In certain applications, such as where space for operation is limited, or where liquids become corrosive upon

exposure to air, the non-rising stem valve is indicated. In this design, the gate or plug is positioned by guide fins, and the stem is threaded to engage the gate or plug. In another pattern the stem is made to pass into a hollow second stem to which the handwheel is attached. The stem or hollow second stem is prevented from rising through the packing gland by means of studs and collars, and therefore, will lift or lower the closure as it is turned.

This valve has the disadvantages of being subject to corrosive attack of the threads and the fouling of the valve by deposits of solids. It also has the disadvantage of not indicating by the position of the stem whether the valve is open or closed.

3. *Outside screw and yoke.* The outside screw and yoke is much used on the larger valves. As the stem does not turn, it can be fastened either rigidly or loosely to the gate or disk; and as the stem rises, its position (either open or closed) can be readily ascertained at a glance. Moreover, the threads of the valve are removed from the liquid in the valve.

The construction is simple. The upper end of the stem is threaded, and is engaged by a handwheel which is threaded through its hub. The handwheel is prevented from rising by means of a yoke and collar, and the stem from turning by means of a slot and fin. Thus, as the wheel is turned, the stem must rise or descend.

The outside screw and yoke has virtually all the advantages of the rising stem, and at the same time keeps its working parts safe from fouling in the liquid stream. It is more expensive to construct than the first two types, but lowered maintenance is usually more than enough to justify the initial higher cost.

Lever-type lifting devices. The gate valve may be operated as a quick-opening valve by lifting the gate with a lever. The action may be either a sliding stem or a cam. The quick-opening valve is good for frequent service, but is not capable of giving the force for either closing or opening that is possible to obtain by use of the thread and wheel; it is, of course, best adaptable to the gate valve, since it normally does not hold positive pressure on the valve.

Valve turning devices. A hand lever or wrench is a simple

and usually adequate device for operating the plug cock or butterfly valve. The lever may be permanently attached to the valve or may be detachable.

Since the lever is usually at 90° to the pipe at the closed position, and since it may be anywhere from 12 to 60 inches in length, it may project into working areas or aisles and create a safety hazard or interfere with traffic. The detachable handle not only removes this disadvantage but often prevents unauthorized persons from operating the valve. On the other hand, the detachable handle is often misplaced and not available when needed. Further, there is always the tendency to use a wrench, often longer than the regular valve handle, to turn the valve. This will apply too great a force on the valve. Valve failures can often be traced to this, or to the inexcusable practice of placing a long pipe over a regular valve handle to assist in moving a sticking valve.

Large plug valves which would require inordinately long and heavy levers to turn them are normally fitted with a gear wheel attached to the valve, which is in turn driven by a worm gear attached to a handwheel. The force thus produced is greater than that which can be easily applied by a lever, but the quick-opening feature of the valve is sacrificed to permit this improvement.

Automatic Operation

Several mechanisms are available to provide automatic valve operation. These are available in designs which allow exit pressures to equal inlet pressures, but prevent back flow with outlet pressures greater than those at the inlet (check valves); allow a fixed outlet pressure less than the inlet pressure (pressure reducing valves); and permit a definite pressure differential between inlet and outlet pressures (pop or safety valves). A completely different type of automatic valve known as a "steam trap" is a device which will permit water to be driven through it, but which closes to the passage of live steam.

Check Valves. The check valve, which permits only one-directional flow, is a widely used valve. It is used mostly as a safety device to prevent material from backing up in a line if the pressure in the system below the valve becomes greater than inlet

pressure. The check valve also prevents one fluid from backing into another line when two or more fluids are supplied to a common point at different pressures. At scores of points in any piping system check valves serve as dispatchers of pipe-line traffic.

The check valve comes in two general patterns; the lift type, which may be either ball, disk, or plug lifts, and the swing check, which is essentially a disk closure. The construction of these valves is that of a globe valve in which the closure is held in place by gravity or by a coil spring and is free to open when the pressure of the fluid on the inside of the valve will force it open.

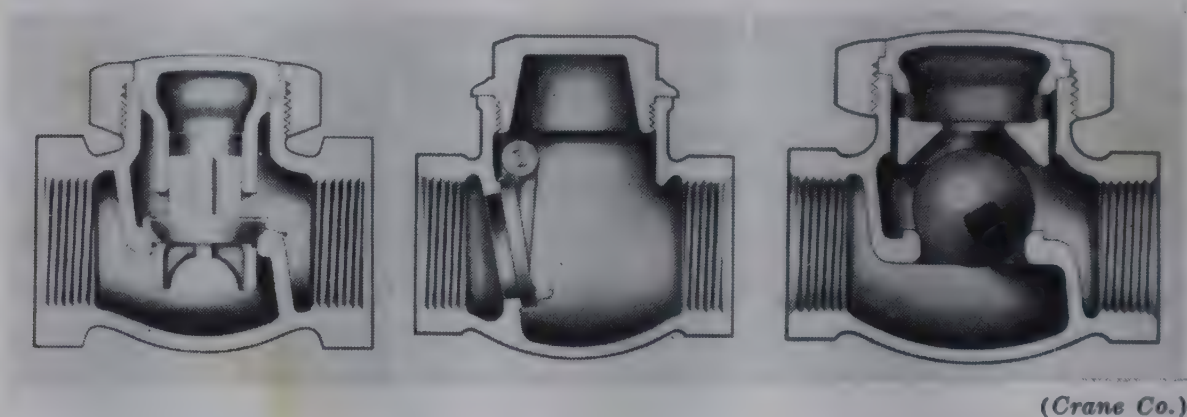


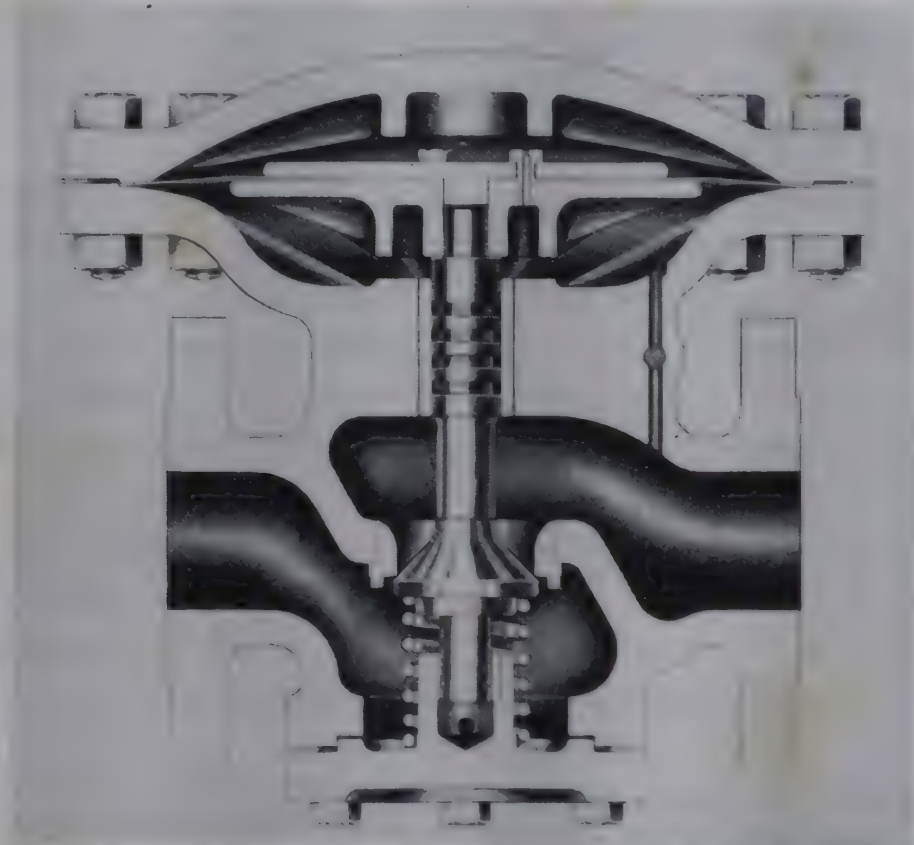
Figure 24. Check Valves. Disk lift, swing and ball lift patterns.

Pressure-reducing Valves. These valves are used widely in industry to supply materials to a system at constant pressure from an inlet line at higher and often varying pressure. Since the temperature of condensation is always directly related to pressure, the pressure-reducing valve is nearly always used for controlling temperatures in dryers and in the jackets or coils of kettles and other steam-heated equipment.

The pressure-reducing valve is a globe-type valve. The closure is controlled by a diaphragm or bellows activated by a difference in pressure on the two sides of the pressure element. The exit pressure is established at will by mechanically loading the diaphragm or bellows. Construction varies considerably but all are of similar basic design.

Safety Valves. If the check valve is loaded with a heavy spring or weighted lever and the exit vented to the atmosphere, the valve can be adjusted to open at any predetermined inlet pressure above

atmospheric. This is the principle of the pressure relief, pop, or safety valve. Many of these valves are provided with whistles or other warning devices activated by the fluid passing through them.



(Fisher Governor Co.)

Figure 25. Pressure Reducing Valve. Section to show operation.

Steam Traps. Steam traps, which have the function of allowing water to pass but retaining steam, are almost always used for the automatic removal of condensed water from any steam-heated unit. These devices are made in a wide variety of patterns, there being bucket traps, float traps, inverted bucket traps, temperature-activated traps, and many other types. All have one feature in common—a compartment in which condensate can collect, and an automatic release valve which will open when the compartment is filled or partially filled with liquid. The valve may be activated by a float which rises or falls as the condensate drains into the trap, or by a pressure diaphragm which operates by the difference in temperature between the condensate and the live steam.

Remote Operation

Valves frequently may have to be so located that manual operation of handwheels, levers, or wrenches becomes difficult, if not impossible. Remote operation in such a situation thus becomes necessary. This is achieved through mechanical, hydraulic, or electrical methods; the first is better adapted to very short distances, the second to intermediate distances (up to possibly 800 feet), and the third to much greater distances.

Mechanical operation. Valves must sometimes be located behind piping or panels, too low for convenience, or below the operating floor. For operation of such valves, simple extension of the stem will often suffice. This is the simplest solution to the problem of remote control. Valves too far overhead to be reached may be operated by means of spur gears, worm gears, or sprocket and chain drives.

Hydraulic operation. A satisfactory arrangement for valve operations is one in which the handwheel and threaded stem of an ordinary valve is replaced by a rod which is attached to a piston operating in a pressure cylinder. By allowing gas or liquid under pressure to flow into the cylinder above or below the piston, the valve can be closed or opened at will. It can be stopped at any intermediate position between fully open and fully closed.

The valve cylinders are normally operated by a manually controlled multi-port plug valve (pilot) through which the hydraulic fluid can be introduced to the cylinder, and simultaneously drained from the opposite end of the cylinder back into the fluid storage chamber.

The difficulty in moving hydraulic fluids great distances through fairly small tubes is the factor limiting the distance for effective use of this type of control.

Electrical operation. Two methods for the electrical operation of valves are available. In one of these, a solenoid or magnet provides the activating force; in the other the mechanism is driven by an electric motor. Both normally provide only wide open or completely closed service, with no intermediate opening possible. The solenoid is energized to open the valve and the valve is closed by a spring when the current is cut off, or vice versa. The direction of operation of the valve will normally be such that it

is necessary to operate the solenoid for as small a portion of the total time as possible. By limit switches located on the motor shaft and against which a worm is forced when the valve stem reaches the end of its travel, the motor for turning the valve stem is cut off as soon as the valve is either opened or closed, and operates only while the valve stem is actually in motion.

Instrument Control

There is a prevailing trend to make valves, even those remotely controlled, responsive to automatic control by instruments. These instruments may measure any one of any number of elements and translate the results into automatic control of hydraulic or electrical circuits, which in turn operate the valves. Such controls are generally expensive, but are so effective and so free from the erratic control of manual operation that they are receiving much attention. Many processes today are becoming "push button" in character.

TECHNIQUES FOR MOVING GASES

Most of the problems of the movement of gases are solved by methods similar to those used for liquid transportation. The problems introduced by high viscosity are largely eliminated in the movement of gases, but are replaced by the necessity of handling compressible substances, of moving materials in which there are great variations in density, and of handling materials which are frequently at higher temperatures than are normally encountered in the transportation of liquids. Further, since gases have much lower densities than liquids, gas-flow machinery, although similar in design, must be much larger in size and capacity in order to move equivalent masses of materials.

Leaks are often difficult to detect when a gas having no odor or color is escaping into the atmosphere. Flammable gases are likely to be explosive and therefore more dangerous than low-volatility liquids. The hazards of handling toxic gases are more serious than in the case of toxic liquids. Corrosion may be as severe in gases as in liquids, and it may be just as essential that no atmospheric moisture be allowed to reach a gas to produce

corrosive mixtures as it is that moisture be prevented from reaching certain liquids.

Normally the handling methods used for liquids are equally applicable to gases, particularly in the case of pipe, fittings, and valves. The only equipment required for moving a gas which differs in more than minor detail from that for moving liquids is the pumping unit. Therefore, gas pumps and blowers are the only equipment used for the movement of gases to which attention need be called.

GAS PUMPS

Gas pumps, in general, have their counterparts in liquid pumps, but some have major differences in design and operation. Gas-moving devices may be roughly separated into classes according to the pressure developed, although frequently a device may easily fall into more than one class merely by changing speed, valve settings, or other minor adjustments not affecting general design. The four classifications are as follows:

Lowest pressure: Fans	Axial-flow fans
Up to about 5 in. water	Centrifugal fans
	Stacks (natural convection)
Intermediate pressure: Blowers	Centrifugal blowers
Up to about 20 in. water, or on special designs, to 60 in. water	Rotary blowers
High pressure: Compressors	Centrifugal compressors
	Liquid-piston compressors
	Rotary compressors
	Reciprocating compressors
Vacuum pumps: Exhausters	Rotary pumps
	Reciprocating pumps
	Diffuser pumps
	Jet ejectors

Fans. Most fans deliver large volumes of air at low pressures. Their use for ventilating is perhaps their most important application, although they have numerous uses for industrial cooling, for the circulation of gases through chemical equipment, and for many others where pressure limitations will permit.

Axial-flow fans may take several forms. One which is most familiar is the ordinary electric ventilating fan. The variations in form reflect the shape and number of fan blades, and whether or not the unit has a housing. The so-called disk fan has blades which almost coincide with the plane of rotation. Other axial-flow fans have blades which are scientifically designed to deliver the maximum amount of air with the greatest possible efficiency.

Fan housings serve to increase fan efficiency. One of the methods of effecting this increase is to place a venturi-like housing around the fan and to add inlet or discharge guide vanes or both to reduce turbulence losses in the fan.

Centrifugal fans normally are simplified versions of the ordinary tangential-discharge scroll-casing centrifugal pump. The impeller may have straight blades or blades curved either backward or forward. Many of the larger centrifugal fans may also have depths of 4 or 5 feet or more (length of the blades parallel to the shaft). The so-called conoidal fan has blades curved forward near the inlet and backward at the tip. This design is said to give a fan which is non-overloading. A multiblade fan with reasonably short but numerous blades located near the perimeter of the drum-shaped support which holds them is also available.

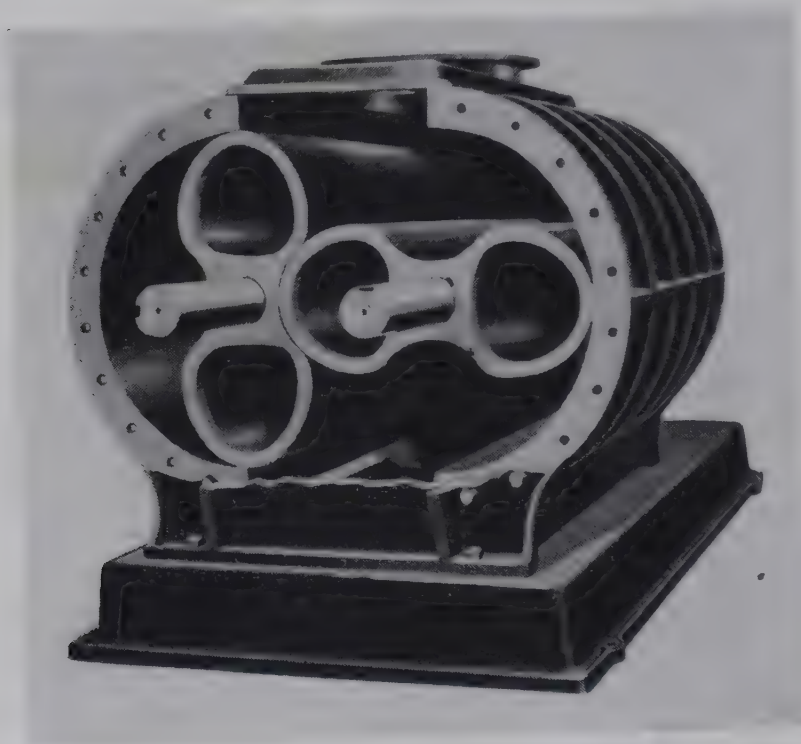
Delivery of gas per unit of power input is about the same for all centrifugal fans. The specially curved blades and multi-blade designs are better adapted for the somewhat higher pressures developed by this type of fan.

Stacks should not be overlooked as a possibility for the movement of gases. The stack functions by the rapid upward movement of a column of warm (low density) gas which is contained within the stack. Although the stack moves the gas without use of power, climatic conditions may seriously affect and vary the pressures developed, and therefore, the volume of gas moved by the stack.

Normally a power-driven fan is much more reliable than a stack, and is much cheaper to install. However, if gases are hot and if it is desired to raise them to a high level so they can be adequately diluted by the atmosphere before they reach the ground, a stack is necessary. Smelter stacks are a good example of this application.

Blowers. Higher pressures than those developed by fans are often necessary to move gases through absorption towers or other intricate chemical equipment. Devices for this requirement may be either centrifugal fans arranged to operate at higher speeds, or some type of positive-pressure blower.

If the ordinary centrifugal fan is more carefully balanced so it can be run safely at speeds up to 3600 rpm rather than at the



(Roots-Connorsville Blower Corp.)

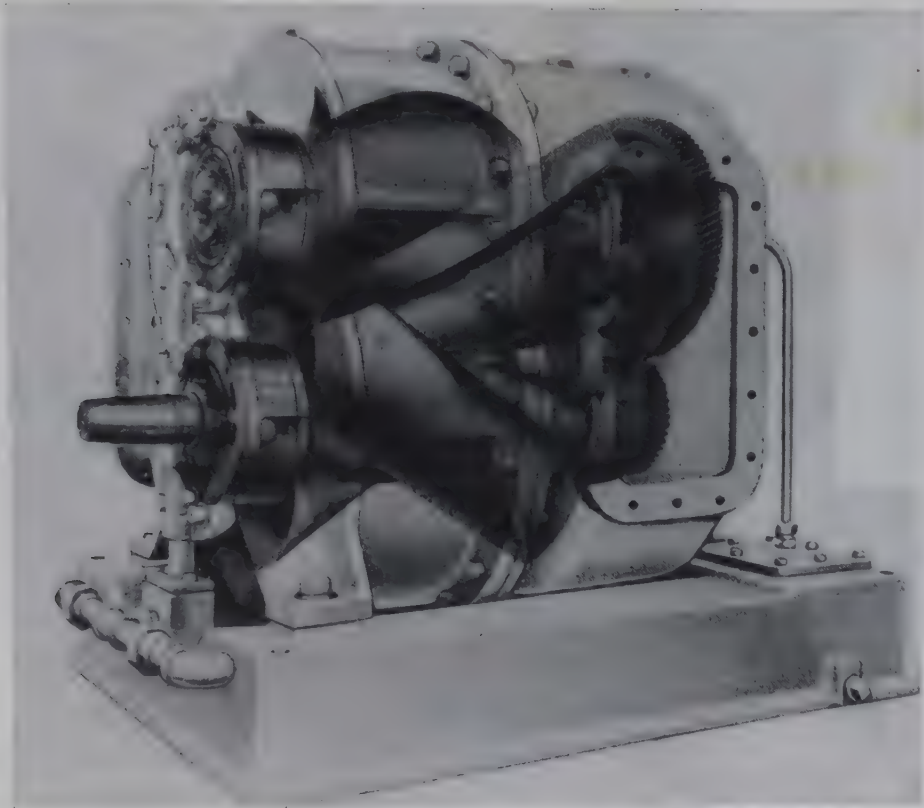
Figure 26. Rotary Blower. Cycloidal type. End plate removed to show rotors.

speeds below 2,000 rpm used for most centrifugal fans, and if the blades are properly shaped, and clearances between impeller and casing made smaller, centrifugal fans become *centrifugal blowers*. These will develop pressures up to 5 psi.

Rotary blowers are available in any of the several patterns of gear or rotary pump described under liquid pumps. The type most frequently used is the cycloidal blower which, in reality, is a gear pump with two teeth on each gear. A new positive displacement blower having much more intricately shaped rotors than those

of the ordinary cycloidal blower has been recently introduced. A number of advantages are claimed for this unit.

This blower, as well as the other rotary types, such as the sliding vane, rotary plungers, and others, must be adequately lubricated to prevent leakage of gas around the impellers. This may limit the use of the blower if a gas which cannot be contaminated



(Read Standard Corp.)

Figure 27. Axial-Flow Positive-Displacement Blower. Phantom view.

by lubricants is being handled. These blowers are capable of delivering gas at pressures up to 10 psi.

Compressors. Pressures well in excess of several hundred psi are often required in plant practice, and pressures up to 15,000 psi necessary in some instances.

Centrifugal Compressors. If the centrifugal blower is operated at high speed, and with close tolerances, and is arranged to have two or more units operating as a multi-stage machine, pressures in excess of 100 psi can readily be obtained. The multi-stage com-

pressor, like the multi-stage pump for liquids, has a large capacity, but it is too expensive to be used for anything other than this type of service.

The two-lobed and other *rotary compressors* may be used in multi-stage arrangements to give higher pressures. The design must be carefully worked out in the multi-stage rotary compressor to provide stages of the proper size to handle the smaller volumes of gas as its pressure is raised.

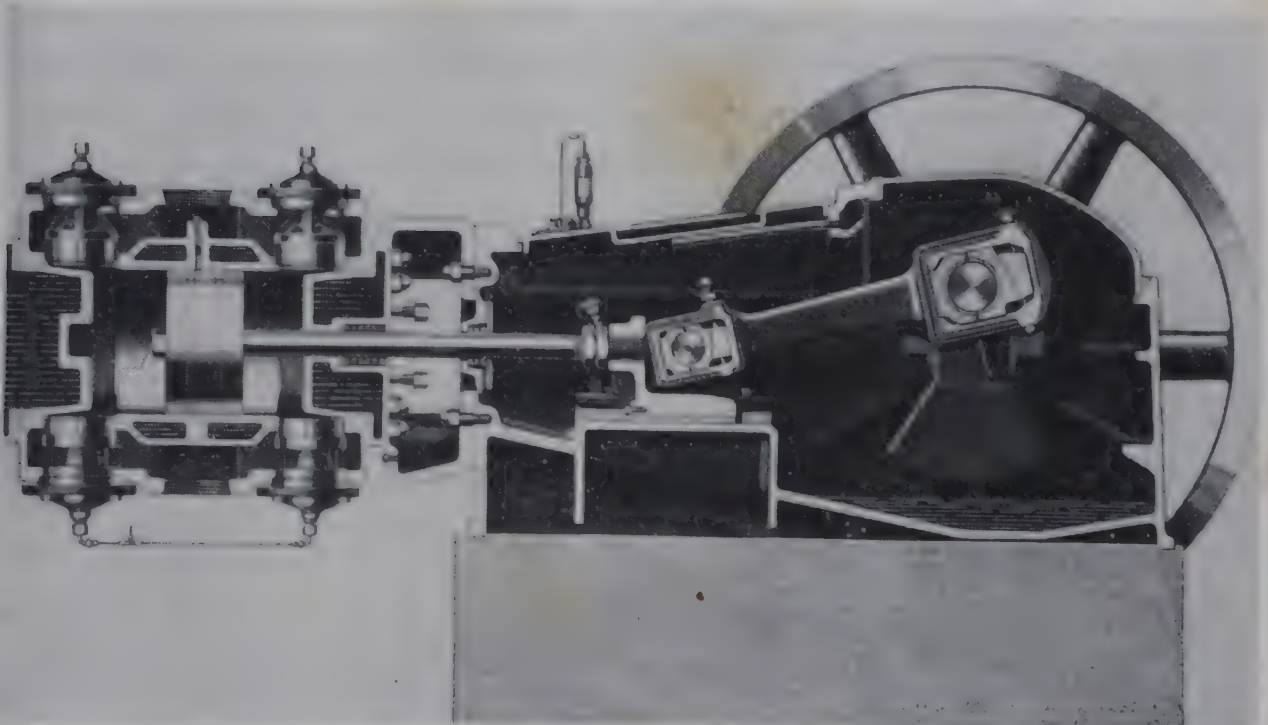
Liquid-piston Compressors. A novel compressor makes use of the principle that if a liquid is whirled at a high rate of speed it will tend to distribute itself over the inside surface of the casing in which it is being whirled, and will be held there by considerable force. This pump has an elliptical casing, and a series of impeller blades which are rotated as are the blades of a rotary pump. The blades force the liquid out along the casing and hold it there by centrifugal force as they are rotated. At the same time there are compartments formed between the blades which go from maximum to minimum volume for each half-rotation, reversing each 180° . By means of slip plates each compartment is made to communicate with inlet or outlet passages as the compartment is increasing or decreasing in size.

These pumps have been very successful and are widely used for compressing gases to pressures of 5 to 150 psi. They may require liquid return traps for dropping out the entrained hydraulic fluid and returning it to the compressor. This compressor has considerable use in those chemical plants where air free from dust, bacteria, oil or grease is essential. The liquid thoroughly washes the gas as it passes through the pump, and since the pump is lubricated by the fluid in the pump rather than by oil, there is no chance for contamination of the air stream.

Water as a sealing fluid may be replaced by any one of a number of other liquids when the occasion demands. An example of this is the use of this type of compressor for moving dry chlorine wherein the pump sealing liquid is concentrated sulfuric acid.

The *reciprocating compressor* can develop very high pressures but handles a relatively small volume. The high pressure (100 psi and up) reciprocating compressor is nearly always a multi-stage unit, having up to four stages for the higher pressures. Since

considerable heat is developed as the gas is forced into successively smaller volumes, the reciprocating compressor is normally fitted with air or water-cooled cylinder walls, and has air or gas inter-coolers between each stage. Each of the cylinders through the several stages must, in turn, be made smaller to provide the correct volume to receive the compressed gas.



(Ingersoll-Rand)

Figure 28. Reciprocating Compressor. Horizontal, single stage, duplex pattern, water cooled.

Evacuators

The problems of producing a vacuum are mostly concerned with machines capable of handling almost astronomical volumes of gas. For example, a pound of air, which occupies about 13 cubic feet of space at normal pressures, will occupy about 10,000 cu ft at one mm pressure, and approximately 1,000,000 cubic feet at ten microns. The techniques of high vacuum production in the volumes necessary for many operations have been only moderately successful. The devices now available are inadequate to meet all the requirements.

Any of the rotary compressors or reciprocating compressors can be used as evacuating pumps. The rotary pumps are frequently lubricated and sealed with mercury for high-vacuum service. The

high pressure, multi-stage feature is not as important as high capacity for vacuum service. Since a certain mass of material is required for the centrifugal compressor to operate, it is not successful as a vacuum pump.

The one pump which has proved to have sufficient capacity to handle large vacuum evaporators or dryers is the condensing steam-jet ejector. A primary ejector is set up by high-pressure steam being directed through an aspirator; a vacuum is then struck, and held by cool water flowing past a second aspirator and into a barometric leg. The barometric leg is a pipe longer than the prevailing atmospheric pressure expressed in feet of water, and consequently will tend to maintain a vacuum approaching the vapor pressure of water. A third stage consisting of a second steam-jet aspirator will further improve the operation with the additional use of steam.

Barometric condensers, a somewhat simplified version of the condensing portion of the jet ejector, are also useful, as is the noncondensing steam jet type.

An ordinary surface condenser which will condense the vapor, together with a pump to remove the condensed liquid and a small vacuum pump to draw off the noncondensibles, will also usually be satisfactory for evaporator operation. This is necessary if the vapor from the evaporator is to be salvaged in undiluted form.

3 : STORAGE OF MATERIALS

Storage Techniques for Solids

- Outdoor storage**

- Indoor storage**

- Special storage problems**

Storage Techniques for Liquids

- Reservoirs**

- Tanks**

Storage Techniques for Gases

- Cylinder storage**

- Low-pressure holders**

- High-pressure holders**

- Low-temperature holders**

- Underground storage**

The storage of materials is a vitally important factor in the successful operation of a chemical plant. The major reason for requiring storage facilities is to assure continuous operation. It is usually quite expensive to shut down a plant for any reason, and it is annoying, to say the least, to have to do so because of failure to obtain and store the proper quantities of materials. Yet it is difficult to decide how much material should be stored because it is expensive to move into and out of storage and to purchase, install, and maintain storage facilities and because stored materials represent idle operating capital. The amounts considered adequate may vary from enough to meet consumption requirements for as little as twenty hours to as much as a year.

Irregularities of supply may be caused by (1) great fluctuations in production, as, for example, in grain crops; (2) failure of transportation, either natural and expected (as the winter cessation of the Great Lakes transportation system), or accidental and unexpected, such as flood, storms, wrecks, strikes, and other contingencies; (3) failures of production, such as strikes, mechani-

cal failures, fires, explosions, or other difficulties which may prevent a supplier from meeting contractual commitments.

Storage facilities may also have economic value by permitting purchasing departments to take advantage of propitious buying conditions. Prices are usually lower if materials can be purchased in larger units; if they can be purchased as they are produced, regardless of the fluctuations of production; or if they can be bought under generally favorable market conditions.

Storage facilities of some size are therefore almost always required and always should be considered in the planning of any process or operation. The most profound differences in storage requirements are occasioned by the nature of the material to be stored—whether it is a solid, a liquid, or a gas.

STORAGE TECHNIQUES FOR SOLIDS

The selection of storage facilities for solids must include consideration of such factors as:

1. Chemical and physical resistance or action of materials exposed to:
 - a. Weather
 - aa. Sun
 - bb. Rain
 - cc. Atmospheric moisture, oxygen
 - b. Biological attack
 - aa. Bacterial
 - bb. Molds and fungi
 - cc. Insects
 - c. Natural deterioration
 - aa. Chemical
 - bb. Physical
2. Flammability or explosive character of material
 - a. External ignition
 - b. Spontaneous combustion
 - c. Speed of combustion
 - d. Difficulty of extinguishing fire
3. Toxicity of materials
4. Size of particles
5. Density and weight of individual particles or units.

6. The necessity for and possibility of "first in-first out" storage
7. Flow characteristics of materials
8. Damage to material by rough handling or heavy pressures in storage
9. Value of material being stored
10. Amount of material to be stored
11. Storage areas or facilities available
12. Equipment available for moving material in and out of storage
13. Maximum amount of money which can be allocated to cost of storage

For storing solid materials there are the possibilities of open storage on the ground; open storage on pads, rails or other prepared underfootings; covered storage on the ground; covered storage on pads or floors; open piles in enclosed warehouses, bins, or silos; air-conditioned, cooled, warmed, or dry storage; refrigerated storage; and storage in a controlled atmosphere.

Outdoor Storage

Open Storage on the Ground. If a material is cheap, must be stored in great quantity, and need not be kept dry, open storage on the ground is universally employed. Materials such as coal, limestone, cement rock, clay, ores, and even wood, pig iron and other materials are stored in this fashion.

The ground on which material is to be stored should be well drained, and the storage and surrounding areas treated with plant killers to eliminate an unsightly appearance and to prevent accidental fires from being set by matches or burning brands carelessly dropped in dry vegetation around the base of piles of combustible material.

There is always a tendency, especially in open storage areas, to make profitable use of transportation facilities by storing materials in huge piles, the total plant supply of any one material often being stored in a single pile. This method is acceptable only for noncombustibles or for materials which do not deteriorate in storage. Many fire insurance companies will not insure large piles

of combustibles except at exorbitant rates. Also there is always the risk of having a plant shut down by loss of materials.

Storage areas, therefore, if holding combustibles or materials which deteriorate in storage, should be divided into small sections, each of which can be cleared of stored material before refilling, and which are separated by adequate fire lanes from other piles of similar materials.

Open Storage on Prepared Footings. The bottom layers of many types of materials may suffer unusual damage by exposure or by chemical, insect, or microbiological attack if the pile rests on the ground. Steel rails, for example, which are seldom stored indoors after they leave the rolling mill, are always stored on old rails or on ties which will keep them from contact with the ground.

Decay in a material like pulpwood is very serious; sometimes a total loss is sustained in material stored in contaminated areas. Storage areas for such material should be completely cleaned after being emptied; decontaminated, if possible, by insecticides and bactericides; and a new surface of fresh cinders spread over the area before a new pile of material is stored on it. It is even better, in many cases, to lay concrete rails or other supports to keep the bottom layers completely off the ground and to allow air circulation under the pile of stored material. Storage areas entirely surfaced with materials such as concrete or asphalt usually more than pay for themselves in savings.

Covered Storage on the Ground. Materials which are damaged by rain or sunshine, but are otherwise little affected by the weather, are normally stored under cover. Actually a roof is all that is necessary, but such a building, even one with an earth floor, usually has curtain walls to keep out driving rains. Walls also reduce the danger of losing a roof in a high wind. Fertilizer materials are nearly always stored in this way.

Covered Storage on Prepared Footings. Many plants are located in low shoreline areas, where ground water may be close to the surface. In such areas, and in any other where contamination of materials is encountered, or their deterioration accelerated by storage on the ground, materials should be placed on floors which may themselves rest on the ground. Consideration must

always be given to the safe loading capacity of the floors, and these capacities must not be exceeded.

Indoor Storage

Warehouse Storage. The storage of materials in loose piles in warehouses differs in no way from the method or restrictions of covered storage on prepared footings. Since the warehouse is likely to be tighter, forced ventilation may be required to keep the atmosphere free of dusts and fumes, either for safety from fire, or for good housekeeping, or both.

Warehousing is, of course, the only answer to problems of storing materials in bags, boxes, or other packaged units. In arranging warehouse storage, many features of the materials and of general warehousing requirements must be kept in mind. Adequate aisle space, accessibility of fire extinguishers, and good housekeeping should be considered, along with such items as proper ventilation, sufficient lighting, and sufficiently strong floor supports for the materials to be stored. Material must be piled carefully to prevent toppling and the breaking of boxes or crates at the bottom.

Bin or Silo Storage. Dusty materials, materials which are likely to be seriously affected by weather, toxic materials, and many others which must receive special treatment while in storage, can be handled successfully in bins. Bins also provide a means for "first in-first out" storage.

One of the most bothersome features of bin storage is the tendency of many solid materials to form an arch in the bins and to refuse to drop into the discharge. Many devices have been patented or have been tried in an attempt to prevent this arching. The shape of the walls themselves appears to be the best solution. Arching is minimized if the walls slant outward from the top down to a point just above the place where the material is to be removed.

Another factor which influences the style of a bin considerably is the necessity for giving the floor a slope greater than the angle of repose of the material being stored so that all contents will drop from the bin as it is emptied. For this reason, bins are likely to be tall and narrow with steeply sloping bottoms. The many

grain elevators throughout the country are good examples of solids bins. Bins are nearly always supported far enough off the ground or floor to permit the installation and operation of conveying equipment under them.

Special Storage Problems

Many materials are of such a nature that they will not respond to ordinary storage treatment. Foodstuffs which require refrigerated or temperature-controlled storage are of this character. New problems have recently been created in the storage of frozen foods which must be kept at temperatures well below the freezing point.

An unusual storage requirement is presented by cotton seeds. These are received during a short interval of time and are processed over several months. Stored in large bins holding several thousand tons each, cotton seed will develop heat in storage which will cause the oil to turn rancid; consequently, the bins are fitted with perforated bottoms through which air may be circulated at any time the temperature starts to rise.

Many other special problems of storage are occasioned by the rather unusual properties of some materials. For example, a material which hardens on exposure to the air must be stored where power shovels, or even blasting, can be used to take it out of the pile safely.

Particular attention should be paid to existing fire codes affecting the storage of flammable substances. Where flammable or explosive substances are stored, all electrical fixtures and wiring should conform to the National Electrical Code for explosion-proof wiring. Tight enclosures, dust collection systems, and cleanliness can do much to reduce the danger of dust explosions. Maintenance of a relative humidity of 60 to 70 per cent is usually sufficient to keep static electricity from building up to a sparking level. If this humidity cannot be maintained or is not allowed because of the nature of the material in storage, adequate grounding must be provided to dissipate static charges.

In many cases, the material stored will present varying degrees of hazards which depend upon its state. Thus, facilities for the quick exhausting of dangerous dust concentrations or the contin-

uous ventilation of storage compartments and elevators should be provided.

In the construction of storage warehouses it is necessary that the floors be of sturdy construction, fireproof, and perfectly level. Uneven floors may lead to the toppling of piles of stored materials with subsequent damage to the contents and an untidy condition in the area. Proper color coding of the maximum height to which material may be piled should be encouraged. The same coding should extend to the floors and any moving equipment used in the warehouse in order to designate limits of piles and stacks and to identify dangerous moving equipment.

All aisles leading to sprinkler valves and fire extinguishing equipment should be kept clear. Materials should not be piled any closer than 18 inches to sprinkler heads to assure adequate wetting of the area under the head in case of fire.

Care should be taken not to stack cartons beyond the strength of the lowest layer. They should also be tiered back to prevent toppling. Loaded paper cartons should be kept dry, as any moisture will weaken the pile.

Material in bags should be cross-tiered and should have the mouth of the bag toward the inside of the pile. In removing material from the piles, care should be taken that the bags are removed only from the top.

Barrels and kegs should be given adequate support by the use of planks between layers.

Adequate storage areas should always be available. Inadequate space for storage makes for inefficiency in operation and is the immediate source of many injuries. It increases the difficulties in handling materials to and from storage, encourages bad house-keeping, contributes to fire hazards, and may cause overloading of floors beyond their calculated factor of safety.

STORAGE TECHNIQUES FOR LIQUIDS

The storage of liquids does not ordinarily offer nearly the same degree of choice of methods as does the storage of solids. Most liquids must be stored in tanks. The several factors which govern the type of storage tanks selected and the material from which they are made are as follows:

- a. Corrosive properties of liquid
- b. Vapor pressure of liquid
- c. Damage, if any, on exposure to rain, sun, etc.
- d. Flammability of liquid or its vapor
- e. Value of the liquid being stored
- f. Sensibility of liquid to changes in temperature
- g. Quantities to be stored
- h. Possibility of contamination by walls of tank, ease of cleaning, etc.

The techniques available for liquid storage involve two types of equipment: reservoirs (depressions in the earth which may or may not be lined) and tanks, which may be open or closed.

Reservoirs

Reservoirs are widely used for liquid storage and would probably be used more were it not for the fact that in small sizes, if lined, they are usually somewhat more expensive than tanks of equal volume; also, leaks are difficult to discover and repair.

Earthen Reservoirs. Unlined reservoirs, such as those used in many water storage systems, have little use other than for the storage of raw water, which, on the tonnage basis, is exceedingly low in value. Contamination by the underlying soil and small losses through leakage and evaporation are of little consequence. Several oil companies are engaging in experiments in the use of underground reservoirs made by dissolving cavities in salt deposits.

Lined Reservoirs. Reservoirs lined with concrete or with other materials which will prevent the seepage of liquid away from the reservoirs or will retard contamination from the walls have considerable use. These are frequently used for the storage of purified water, many liquid chemicals, or solutions which must be kept in large quantities.

Tanks

Tanks are important not only for storing liquid raw materials for plant consumption, but also for smoothing fluctuations in production and supply of intermediate products, and for storing finished liquid products until they are packaged or transferred to containers for shipment. In addition, tanks are frequently used

for reaction vessels. There is virtually no chemical manufacturing plant or process industry which does not have extensive need for tanks. They are available in a wide range of types and materials of construction.

Because of its low cost and ease of fabrication, storage tanks are usually built of steel. When steel is subject to chemical attack, a steel tank may be lined with plastic, cement, paint, rubber, glass, or any one of several noncorrosive metals or alloys. The whole tank may be constructed also of stainless steel, copper, brass, bronze, nickel, aluminum, or "Monel," or of wood, concrete, brick, or tile, or of brick or concrete lined with acid-proof tile set in an acid-proof mortar.

Wooden tanks are widely used in industry. Many chemical solutions, corrosive to iron or contaminated by exposure to it, may be successfully stored in these. If kept wet by solutions which do not react with wood, or do not dehydrate wood because of high concentration of salts, wooden tanks are quite satisfactory, and usually are somewhat cheaper than those made of some of the noncorrosive metals or those having special linings.

Most nonvolatile liquids are stored in tanks which are open to the atmosphere; a covering on the tank need be added only to keep out rain or dust. Volatile liquids must be stored in closed tanks. Special means must be provided to vent closed tanks as they are filled or emptied, or to relieve pressures built up by vaporization. Some closed tanks are built heavily enough to withstand the high pressures of liquid propane, butane, chlorine, or other liquefied gases. Tanks used for resinous or waxy materials which tend to solidify when cold must be provided with suitable heating coils, especially if located outdoors or below ground level.

Low-pressure Tanks. Most low-pressure tanks are constructed in the form of squat cylinders as large as 500 feet in diameter and as high as 50 or 60 feet. Smaller tanks may be elongated somewhat to take up less ground space per unit of storage volume. There is a tendency, especially in locations where tanks are to be seen by the public, to construct tanks in the form of spheres, spheroids, or other shapes to give a pleasing appearance, and to give maximum capacity with a minimum of steel surface. Many of the newer tanks erected for city water systems are of this type.

In the past, steel tanks were almost always made of riveted plates, but with improvements in electric welding, most of the recently erected tanks have been of welded construction. The average plate thickness for low-pressure steel tanks is about $1/4$ inch.



(Chicago Bridge & Iron Co.)

Figure 29. Municipal Water Storage Tank.

Wooden tanks, generally made of redwood or cypress, are usually cylindrical in shape and are assembled from wooden staves from $1\frac{1}{2}$ to 8 inches thick, cut to a length corresponding to the height of the tank, and bound together by metal (usually steel) tie bands. Where the bands may be corroded they should be kept from contact with the staves, or steel for the banding or tie rods should be replaced by a non-corrosive metal or alloy. Leakage in shapes other than oval or cylindrical is difficult to avoid.

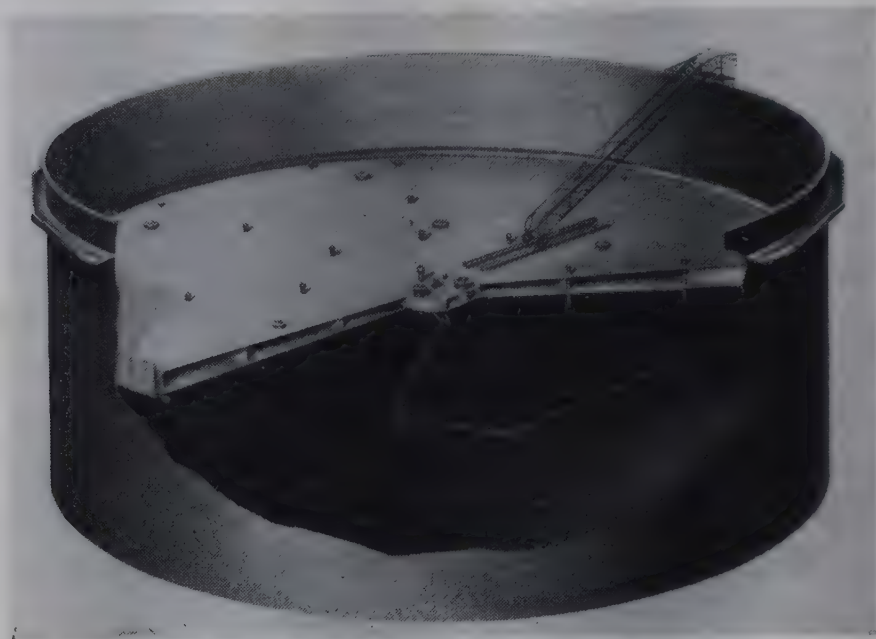
Closed Tanks for Storage of Volatile Liquids. The storage of gasoline and of solvents which volatilize readily has given rise to the need for a tank which will withstand pressure variations from day to night and allow "breathing" without loss of material. Gasoline or light solvents will vaporize to fill the vapor space, and if stored in a tank which communicates with the atmosphere, will lose vapor as the tank is warmed during the day. At night, the vapor tends to condense and draw air into the tank. With daily repetition, the yearly loss from breathing may amount to as much as 30 to 40 per cent of the contents of the tank. The tank is also left filled with vapor as it is emptied, and this vapor is driven out as the tank is refilled. Several thousand cubic feet of vapor driven from a tank may easily represent the loss of a barrel of liquid. As a consequence, many styles of tanks have been manufactured to minimize or completely prevent vapor losses. The features common to all such tanks are that they are completely closed, and are capable of withstanding low pressures.

Water-cooled Tanks. Much of the breathing loss can be prevented if the tank temperature is kept as uniform as possible. If water is plentiful, large sprinkling systems set on the roofs of the tanks minimize temperature changes. Another similar solution is to provide the tank with a dished roof which may be filled with two to three inches of water. This type of tank does not reduce vapor losses on emptying and refilling.

Floating Roof Tanks. A rather novel tank is made which almost eliminates both breathing and filling losses. In this tank, the lid is free to slide up and down inside the tank like a piston in a cylinder, and is dished to trap just enough air to float it on the surface of the liquid. Since there is virtually no vapor space, breathing is almost eliminated, and since the roof follows the liquid surface there are no vapor losses in filling and emptying the tank. The only difficulties with this tank are the added expense of making it smooth on the inside, the cost of the special roof, and the possibility of seepage around the edges of the roof. If erected in an area where heavy rain or snow is usual, it may have to be covered by a second roof to keep water from collecting on the pontoon roof.

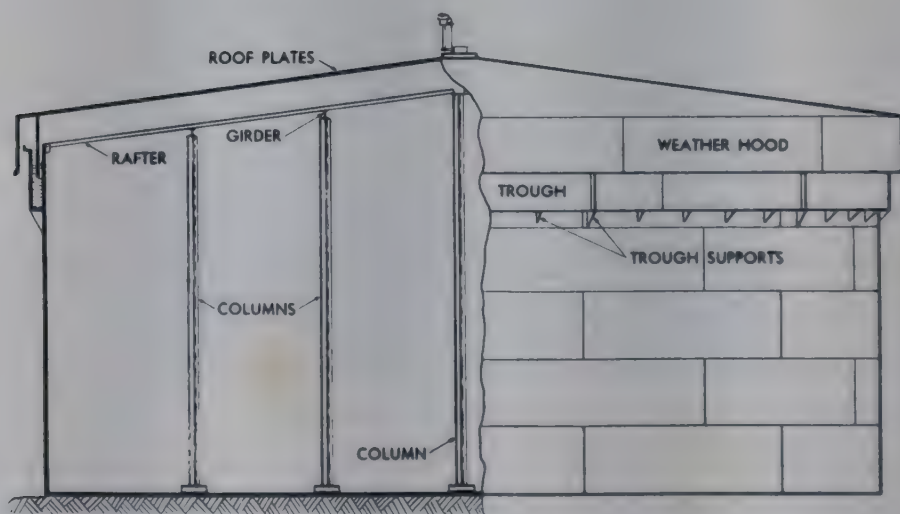
Expansion Roof Tanks. In another tank which will prevent breathing losses the regular fixed roof is replaced by a gas bell

made in the same general fashion as a single-lift gas holder. With standard lifts up to 10 feet, vapor losses by breathing can be entirely eliminated. It effects only a partial saving of filling losses.



(Chicago Bridge & Iron Co.)

Figure 30. Liquid Storage Tank. Double deck, floating roof.



(Chicago Bridge & Iron Co.)

Figure 31. Liquid Storage Tank. Lifter roof.

Vapordome Roof Tanks. The vapordome roof consists of a steel hemisphere mounted at the center of the regular conical or flat roof of a tank. A flexible hemispherical membrane is attached by its outer edge to the inside of the vapordome. The membrane is therefore free to hang down into the tank or to balloon up into

the dome. This permits the air-vapor mixture in the tank to expand and contract without venting vapor to the atmosphere.

Connection of Tanks to Auxiliary Breathing Devices. Several tanks used to store the same material may be connected to a manifold which in turn is attached to an auxiliary gas- or vapor-holding device; thus one expansion tank may act as a vapor



(Chicago Bridge & Iron Co.)

Figure 32. Liquid Storage Tank. Vapordome roof.

receiver for several ordinary tanks. One or several liquid storage tanks may also be attached to a small low-pressure gas holder, to a collapsible gas bag, or to the newly developed vaporsphere. The latter, similar to the vapordome, consists of a full sphere with the flexible hemispherical membrane attached to its equator. The membrane can thus allow the sphere to be completely filled with vapor or be virtually empty of it.

Medium-pressure Tanks. Tanks able to withstand medium pressures successfully are used where vapor pressures do not appreciably exceed atmospheric pressures. These are not to be mistaken for the ordinary high-pressure tank, for they are much lighter in construction and are usually patterned after the ordinary low-pressure tank. This tank, as well as the water-cooled

tanks and the expansion-roof variety, must be provided with breather valves set to permit gas to escape or air to enter before the safety limit is exceeded. These valves are two-way check valves set to open when the pressure required to lift the particular gate has been reached.

High-pressure Tanks. Commercial-sized tanks capable of withstanding pressures up to 100 psi are available as standard equipment. The higher pressure tanks range toward the smaller sizes.

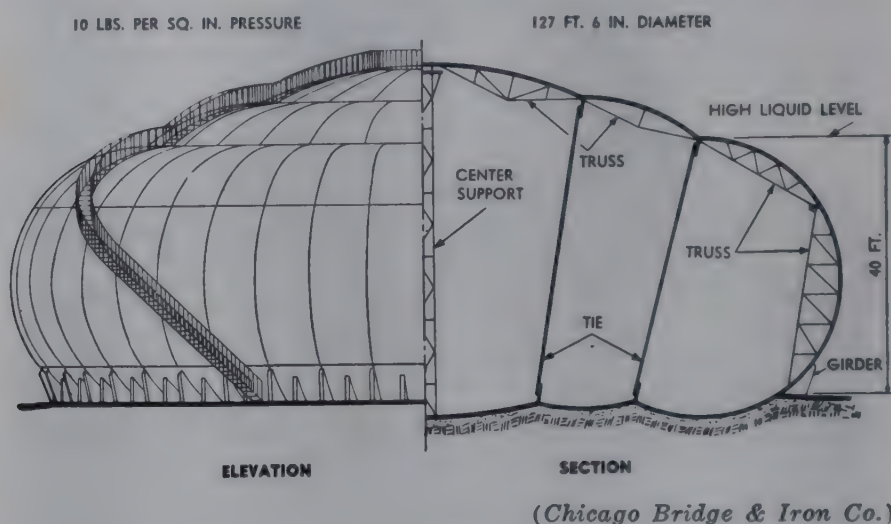


Figure 33. Pressure Tank (Horton spheroid).

Several patterns of high-pressure tanks are now available; more and more interest is being centered on the spherical shape, which is structurally superior to other shapes and will hold the greatest volume of liquid per unit of surface area. Pressure tanks may be purchased in all the following shapes: spherical; spheroidal; hemispheroidal; multispherical; and cylindrical, mounted either vertically or horizontally.

Tanks for pressures greater than 100 psi are built to the specifications of the user.

Special Tanks. Tanks of special design, such as the large, heavily insulated tanks built for storing liquefied fixed gases, and the heated or insulated tanks used for storing liquids of high freezing point, such as waxes, have been developed for many special purposes.

Railroad tank cars are often used as temporary tanks. They are spotted at the proper location near the plant, locked in position, and the contents fed into the plant operation as required. The

expense involved in retaining the car beyond a specified time (demurrage) usually makes this practice uneconomical unless the tank cars are leased to or owned by the user.



(Chicago Bridge & Iron Co.)

Figure 34. Pressure Tanks (Horton sphere).
Capacity 10,000 bbls; diameter 48'; pressure rating 65 psi.

STORAGE TECHNIQUES FOR GASES

Since gas is used in many industrial plants, and is often produced as an intermediate product or manufactured for sale, its storage is important. Because of its low density, the equipment required to store any appreciable quantity of gas is usually quite bulky and somewhat more expensive per unit weight of storage than the tanks used for liquids.

Fewer factors govern the selection of the proper method for gas storage than for the storage of either solids or liquids. The question of corrosion is ever-present, and before it is stored gas must sometimes be freed of water or other materials which encourage corrosion. The quantity to be stored is important, but the most important consideration is, perhaps, the pressure at which the gas is to be used as it comes from the storage holder.

Gases are stored in small quantities in pressure cylinders, either as a highly compressed gas; as a concentrated solution of a gas

in a solvent, as for example, acetylene dissolved in acetone; or as a liquefied gas, such as liquid chlorine or liquid carbon dioxide. Gases may also be stored as liquids in highly insulated containers at temperatures of the boiling point of the gas.

In larger quantities, gases may be stored at low or high pressures at ordinary temperatures, or as a liquid either at medium to high pressures at atmospheric temperatures or at atmospheric pressure and very low temperatures. Underground storage of gas in spent oil or gas fields is a novel and relatively new method which is beginning to be used.

Cylinder Storage

Cylinder storage is limited to very small quantities of gas and is useful, therefore, when only such quantities are needed.

"Fixed" gases, such as nitrogen, oxygen, or hydrogen, are compressed to about 2,000 psi and placed in commercial cylinders which have a cubic capacity of about 2 cu. ft. These cylinders are exceedingly wasteful of steel, since a cylinder weighing 150 pounds or more is required to hold slightly over one pound of hydrogen (about 200 cu. ft. of gas at standard temperature and pressure). These cylinders range in size from this capacity down to about 1/25 cu. ft. actual volume.

Chlorine, sulfur dioxide, carbon dioxide, and other easily liquefiable gases may be liquefied and stored in containers which are similar in appearance, but of somewhat lighter construction than the ones used for oxygen. The ordinary cylinder for these gases will hold as much as 200 pounds of liquefied gas, with a cylinder weight of less than 150 pounds. Cylinders for these materials are also available in a wide range of sizes up to one holding about one ton of gas.

Some gases have the property of being dissolved in remarkable quantities in a liquid or strongly adsorbed on a solid when brought into contact with these materials at slightly elevated pressures, and are released at lower pressures. Acetone will dissolve acetylene in this fashion; hence large quantities of acetylene are stored and shipped in acetone solution. The pressure required on these cylinders is even less than that held on the liquid-filled gas cylinders.

Recent developments in gas liquefaction have made it prac-

ticable to liquefy such gases as oxygen and nitrogen. These gases can be stored and shipped in what amount to large vacuum bottles in quantities well in excess of the weight of the container. The bottles are cooled by the slow evaporation of the gas and are thus kept at atmospheric pressure. They must not be stoppered.

Low-pressure Gas Holders

Low-pressure holders are widely used for storing gas. They are particularly useful if the gas is produced or purchased at low pressures and if it is to be used at pressures up to about $1/2$ psi. This pressure is about the maximum maintained on the gas in this type of holder.

Low-pressure gas holders are constructed in two general types and are built to hold gases at pressures not to exceed a few ounces per square inch. The two general types of gas holders are the water-sealed holder and the so-called "waterless" holder.

Water-sealed Gas Holders. This type of gas holder is made in two styles: as a single-lift, or as a multiple-lift holder. Both are inverted gas bells, the single-lift being a single unit, and the multiple-lift being composed of a series of interlocking collapsible rings. The single-lift holder is built in sizes up to about 300,000 cu. ft. capacity; the multiple-lift up to as much as 5,000,000 cu. ft. Construction is light, the steel sheet used being about $1/8$ inch in thickness. The tanks are guyed and braced on the outside and are supported on the inside by the pressure of gas against the walls. They are kept from bulging by staying on the inside of the holder.

Water-sealed gas holders are normally quite satisfactory and are usually somewhat cheaper to install than the corresponding size of the waterless type. Consequently, if the low-pressure holder is satisfactory in capacities up to 1,000,000 cu. ft., the water-sealed style is almost always used.

Waterless Gas Holders. The waterless gas holder consists of a gas-filled cylinder having a floating lid which rises and falls as the quantity of gas is increased or decreased. Because the walls must be rigid, and cannot be stayed on the inside, they must be built heavier than those of the water-sealed holders.

The floating lid must be guided to keep it from tipping, and

must have an effective seal against the walls to prevent gas leakage. A sealing disk of leather, synthetic rubber, or light steel, and a sealing fluid of light tar or heavy oil are normally used. A light roof to keep snow and rain off the lid completes the construction. The waterless gas holders are probably the world's largest walled tanks, being made in sizes up to 20,000,000 cu. ft. capacity.

A second type of waterless holder has been introduced comparatively recently. In this holder, a semirigid steel disk forms the center section of a movable lid. This lid is attached to the wall of the holder by a limp diaphragm having sufficient slack to allow the lid to travel to the top of the holder or to the bottom. Except for the rigid disk at the center of the diaphragm, the action closely resembles that of the vaporsphere. Guides keep the rigid portion of the diaphragm centered and horizontal, and assure proper functioning of the limp ring or rings.

In the larger sizes the waterless holder is almost as cheap as the water-sealed holder per unit volume and does have some definite advantages. These are as follows:

1. With no water seals there is no necessity for installing steam-heating coils or making other provision to prevent freezing of the seal.
2. Heavy snow on the roof of the water-sealed holder will cause trouble in the operation. This difficulty is not experienced in the waterless type.
3. Ice storms, which may cause the water-sealed holder to become heavy on one side and possibly tip enough to break the seal, do not affect the waterless holder.
4. Gas pressure in the holder is uniform, regardless of how full the holder may be. This is not the case in the water-sealed holder where the gas pressure increases as the holder rises.

High-pressure Gas Holders

High-pressure gas holders are constructed in exactly the same patterns as those described for the high-pressure liquid holders, spherical, spheroidal, hemispheroidal, and cylindrical patterns being available. The structural stability of the spherical shape and the saving in material in its construction make it as impor-

tant for this use as it is for the storage of liquid under pressure. The high-pressure holders are built in sizes up to about 35,000 cu. ft. actual capacity.

High-pressure holders have considerable use in industry, especially for storing gas which is to be used at or near the high pressures maintained in the tanks, or where the gas may be kept liquid at these pressures.

As compared, in general, to the low-pressure holders, the high-pressure types have certain advantages. Some of these are as follows:

1. Per unit weight of gas stored, the high-pressure holder is more economical of space, and sometimes of materials of construction, than is the low-pressure holder.

2. The high-pressure holder is much more pleasing to the eye than the larger, bulkier, low-pressure unit. It is smaller, freer of outside structural members, more artistic, and can be kept cleaner. Its use for gas storage in residential districts is thus indicated.

3. The high-pressure holder needs less inspection, is less likely to leak, and requires, in general, less maintenance than the low-pressure holder. Its use in remote locations is a result of this advantage.

Balanced against these advantages are several rather serious faults.

1. Unless the gas is to be used at high pressure, it is expensive to compress all the gas being made. This would be especially serious in a coal gas plant, for example, where the gas holder floats on the line to absorb fluctuations of supply and demand.

2. The high-pressure gas holder has a fixed volume, and cannot, therefore, be completely emptied of its contents by opening a valve. This fault is eliminated in the vaporsphere.

3. Water will condense from a gas, such as a manufactured gas, when the gas is compressed and cooled to atmospheric temperature. Since no method is available for resaturating this gas, the volume delivered to the consumer when the gas is re-expanded is less than the volume before compression.

4. Condensed water may settle in the holder and may, in winter, accumulate as ice in the bottom of the tank. Even in summer this water must be drawn off occasionally, and the corrosion induced by this moisture is always likely to be serious.

Low-pressure, Low-temperature Gas Holders

Large tanks, built on the same principle as the small vacuum bottle, have been constructed for storing oxygen, nitrogen, methane, and ordinary fuel gas. The tanks are steel shells, very thoroughly insulated to permit the interior to remain at the temperature of the boiling point of the gas. Except where the gas is to be pumped to other tanks for transportation as a liquid, there is some question as to whether it is profitable to compress and liquefy the gas for storage only. It does, of course, save storage space, and this, together with a saving in the initial expense of huge gas holders, might justify the added expense of compression.

Underground Storage

The possibility of storing gas in old oil fields is being thoroughly investigated. The exhausted San Joaquin Valley oil field has a probable storage capacity of 2 billion cu. ft. with a 1 billion cu. ft. backlog. With this type of storage, a large volume of gas could be stored in the summer when demand is light and used in the cold winter months without the necessity for the construction of expensive gas holders, or the installation of gas pipe lines large enough to meet peak demands.

SECTION II

THE PREPARATION OF MATERIALS FOR REACTION

4 : SIZE REDUCTION

Size Reduction of Solids

Rock and other friable solids

Fibrous materials

Size Reduction of Liquids

Size Reduction of Gases

Many solid materials, as they come from the mine or quarry, or from some other operation or producer's plant, are not in a suitable condition for reaction. The particles may be highly irregular in size, much too large to be handled with ease, or so massive that reaction would be immeasurably retarded if penetration through the piece had to precede it.

Reactions of solids take place chiefly on the surface; therefore the greater the area of the surface, the faster the reaction rate, and the more profitable the operation. Further, if the pieces of material vary in size, the reaction of the smaller particles may go to completion while that of the larger particles is still far from complete. Size reduction of solids, therefore, has two major functions: (1) increasing surface per unit of weight, and (2) preparing the material for size classification or regulation.

It is frequently desirable and often necessary to reduce the size of liquid drops to increase surface areas and, therefore, reaction rates. Similarly, gases are dispersed in liquids to form foams or to increase rates of absorption by the liquid.

The choice of a technique by which a body of material may be disintegrated will be influenced by several factors. The most fundamental of these is the physical state of the material to be reduced—whether it is a solid, liquid, or gas. Once this has been established, the decision becomes dependent upon:

1. The maximum size of the piece of material which must be reduced.

2. The physical nature of the material, for example, friable, fibrous, or other.
3. The hardness of the material.
4. The size of the desired product.
5. The rate and quantity of production.
6. The effect of heat on the material.
7. The effect of moisture or other liquids on the material.
8. Explosive properties or toxic properties of dusts.

SIZE REDUCTION OF SOLIDS

The Reduction of Rock and Other Friable Solids

Blasting at Mine or Quarry. The reduction of rocks and minerals to a size which can be received by the crushing and grinding machinery of a process plant begins with blasting in the mine or quarry.

The personnel in a plant organization who are responsible for mining or quarrying operations should recognize the capabilities and limitations of the machinery in the process plant which is to receive their product. They should be held responsible for delivering rock or mineral below a maximum size so that chutes will not be clogged or hoppers of machines jammed by oversize pieces. This phase of crushing operations frequently is unintentionally overlooked, or is neglected by quarry foremen in their zeal to boost production. It is always cheaper to reblast oversize rocks in the quarry than to extricate them from the feed chute of a crusher and then have to blast them or break them up by hand.

Principles of Operation of Size Reduction Machinery. The machines designed for reducing friable solids (solids which rupture along well-defined cleavage lines) employ one or more of the following principles of rock disintegration:

1. *Direct pressure.* The pressure applied to a nut by the jaws of a hinged nut-cracker is direct pressure.
2. *Impact.* By striking a sharp blow, a force much below the fracturing pressure will break a rock. This is a highly important feature of many crushers.
3. *Beam action.* If a flat rock rests across a depression and

a force is applied near the unsupported center section, the rock will fail by tension rather than compression. The application of a much smaller force than is required to break the rock in compression will cause fracture.

4. *Roll action.* The pressure as applied to soda crackers upon being rolled between a wooden roll and a flat surface is a homely but accurate description of this type of action.

5. *Attrition.* If material is rolled over itself or is wiped between hard surfaces it will gradually be reduced by small particles breaking off its surface. This is the action of attrition which is almost always found in fine grinders or pulverizers.

Crushing and Grinding Machines. Machines for size reduction are judged for quality and effectiveness by the amount of reduction, by the regularity in size of the product, by the power consumption per unit of material reduced, and by such items of cost as purchase price, cost of foundations, and installation.

The various kinds of equipment used for the size reduction of rock can be roughly classified into three groups, depending on the size of the product. Primary crushers or breakers, as they are sometimes called, are designed to take rock from the quarry and reduce it to pieces from 2 to 6 inches in diameter; intermediate crushers will take rock up to as much as a foot in diameter and deliver a product down to 1/4 inch in size; and fine crushers, grinders, or pulverizers are designed to accept pebbles up to an inch in diameter and reduce them to a fine dust. Many machines overlap these rough size classifications: others of one size will fall in one class, and the same design in a different size will fall in another.

Virtually all disintegrating machines have three basic parts: (1) the feed chute, or other mechanism, which delivers rock at a speed at which it can be handled by the crushing mechanism, and prevents rocks too large for the machine from entering it; (2) the crushing mechanism, which has two parts, (a) the fixed anvil and (b) the movable crushing device; (3) the opening or means for removing the crushed material as it is delivered. An auxiliary device for returning the oversize material to the crushing elements is frequently a part of the unit.

A feature which should not be overlooked in the design and operation of rock crushers is the so-called angle of nip. In most crushing machines the faces between the anvil and the crushing plate are inclined toward each other. When these surfaces are brought together there is always a tendency for the rock to slip out. In the design of crushing equipment there is a continuous effort at compromise between the safe angle of nip and the necessity for having as wide an opening as possible. The safe angle of nip is never over 32° .

The angle of nip is influenced most by the character of the material being crushed. A smooth, hard particle or a soft, greasy one slips more easily than an ordinary gritty one. Another factor influencing this angle is the character of the rolls or surfaces: those which are worn smooth require a smaller angle. Since the coefficient of friction is reduced by high speed, the more rapidly the surfaces approach one another the smaller the angle must be. Even the way the material is fed may affect it. Dry material has generally less tendency to slip than does damp, but a stream of water may wash away surface slimes and clay and improve the manner in which the machine accepts the feed.

Primary Crushers

All primary breakers are characterized by relatively slow but massive action, tremendous output, and powerful drives. These machines are built in sizes to take rock up to 6 feet in diameter. Care must be taken, however, to select a machine just large enough to match its production against requirements, and to balance its cost of operation against the cost of reblasting in the quarry.

Jaw Crushers. The simplest of the primary crushers is the jaw crusher, which is similar in action to a nut cracker. Crushing action is entirely by direct pressure. The driving force is augmented by large flywheels which build up momentum during the half cycle when the jaws are opening.

The jaw crusher consists of one heavy, ribbed stationary plate which forms the crushing anvil, and a movable plate which moves back and forth to develop the pressure on the rock, which is caught between the two plates when the opening between them

is at its widest position. The movable plate may move on a hinge at the top, as in the Dodge crusher, or at the bottom, as in the Blake design; or it may operate on a toggle joint to give it a rocking motion, as in the Denver crusher.

The crusher hinged at the top is nonchoking, which is a definite advantage. However, as the plates are closed, rock may be pushed out of the machine with considerable force. Since the discharge opening is the point of greatest motion, the product is likely to be quite variable in size.

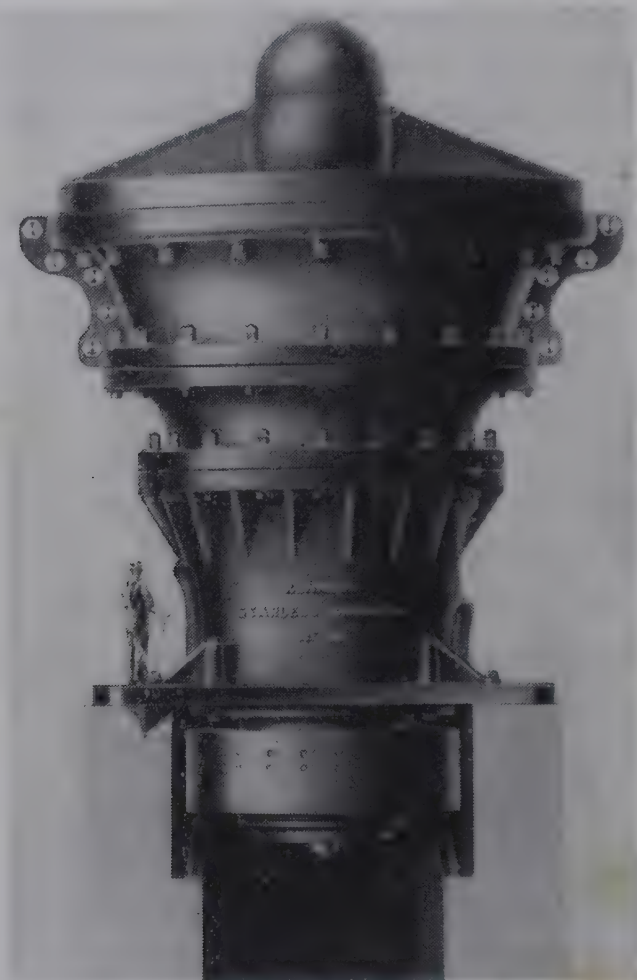
The bottom-hinged Dodge type closes the angle between the jaws as the movable jaw closes, and therefore, has much less tendency to disgorge material fed to it. The product is discharged at the point of least motion and is therefore somewhat more uniform than the top-hinged crusher. However, it is extremely easy to choke this unit completely, so it must be carefully fed to avoid overloading. The Dodge-type crusher has a somewhat smaller capacity than the Blake-type.

The toggle types average the advantages and disadvantages of the opposed basic patterns. There is little other choice between the several styles.

Gyratory Crushers. The jaw crusher is idle for one-half of its operating time while its jaws are opening to receive a fresh charge of rock. The gyratory crusher is arranged to crush material continuously. It consists of a heavy steel cone or plug, pivoted at its apex, and caused to move with a gyrating motion inside a conical housing having walls of slightly smaller conical angle than that of the plug. The material to be crushed is introduced into a cup-like feed hopper and moves down into the space between the gyrating cone and stationary housing as the cone moves away from the point on the wall directly under it. As the opening diminishes in size, the material is crushed. The crushed material drops down and new material takes its place as the space between the cone and housing reopens. Similar action takes place continuously through the whole cycle of movement of the cone.

The gyratory crusher has a high power efficiency and a very high capacity. Large units are capable of producing up to 2000 tons per hour. For small production requirements its capacity may be too large to warrant its use.

Gyrocentric Crushers. The gyrocentric crusher represents a novel manner of making a jaw crusher operate in both directions. In this crusher two curved stationary plates are placed facing one another. Between them is a roll which moves on a cam to give a gyrocentric motion between the two fixed plates. This machine



(Kennedy Van Saun Mfg. & Eng. Corp.)

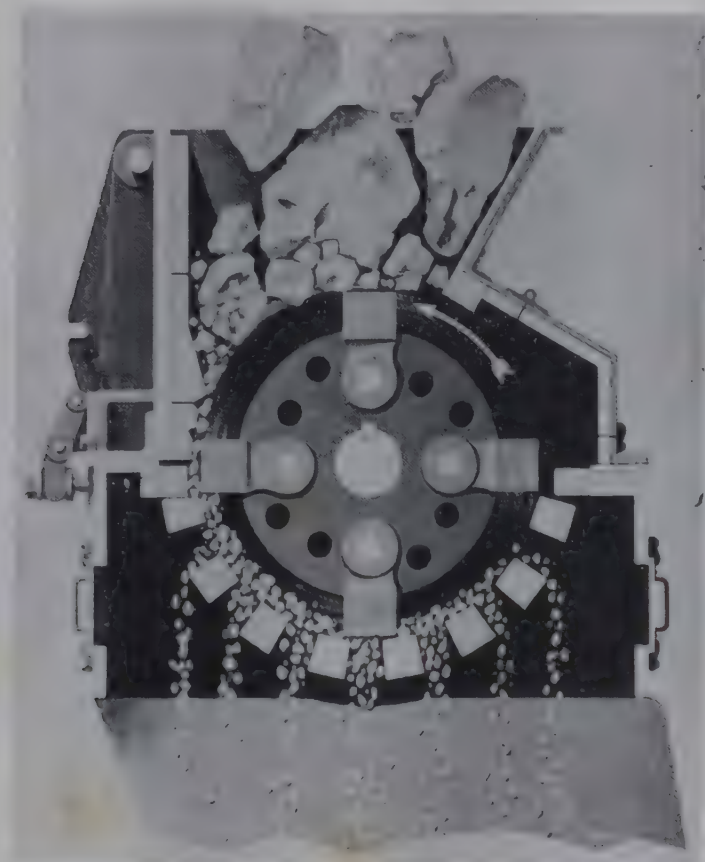
Figure 35. Gyratory Crusher.

is also a large-capacity unit and should be a highly satisfactory crusher. It is not, however, nearly as widely used as the gyratory or even the jaw crusher.

Intermediate Crushers

Both the jaw and the gyratory crushers could, in the smaller sizes, be considered intermediate crushers. A gyratory crusher of a somewhat different design is used as a commercial-type intermediate crusher; jaw crushers seldom are used commercially in this range.

Swing Hammer Mills. Perhaps the most widely used of all intermediate crushers are the several makes of swing hammer mills. These mills are capable of delivering thousands of heavy hammer blows per minute to the rock delivered through the inlet spout. Stones are also caught between the hammers and are violently thrown about and against other stones in the mill.



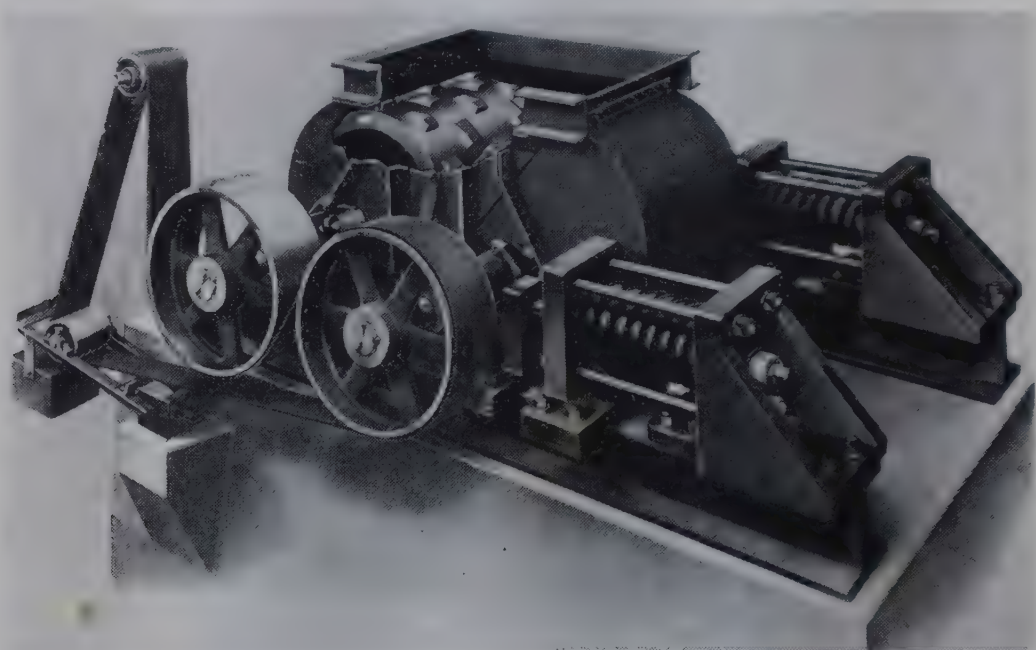
(The Jeffrey Mfg. Co.)

Figure 36. Hammermill Crusher.

The crushing action of the hammer mill is effected by heavy U-shaped hammers mounted on pins thrust through a rotating disk near the periphery. The average hammer mill has three or four such hammers on each disk, and perhaps as many as fifteen or more disks in the mill. All disks are keyed to the same shaft. When the machine is nearly empty the hammers extend straight out from the disks, held in that position by centrifugal force. When rock is introduced it is caught between the hammers and the breaker plate and is repeatedly hit by the hammers until it is broken. The hammers, being pivoted, will ride over the rock if it resists the first impact, and will continue to hit and ride up

and over until the rock is reduced and carried away from the breaker plate.

The bottom of the unit consists of a series of heavy bars set a small distance apart around the perimeter of the casing, or a very heavy grid or screen shaped to fit the casing. Particles fine enough to pass this grating are dropped into the discharge almost as fast as formed. The larger particles are scooped off the grating by the revolving hammers and carried around for further breaking.



(Kennedy Van Saun Mfg. & Eng. Corp.)

Figure 37. Double Roll Crusher. Slugger rolls.

Capacities of 200 tons of rock per hour are not uncommon, and mills are built in sizes to accommodate rock up to 2 feet in diameter and to deliver a product as small as $1/8$ inch. This much reduction is rarely made in a single machine, however.

Roll Crushers. Roll crushers are constructed in several different styles, and in a wide range of sizes. The amount of reduction is never as great in a roll crusher as that obtained in a hammer mill, but all roll crushers are characterized by their ability to produce a fairly uniform product.

Roll crushers are built in both single-roll and double-roll patterns. The rolls are made with either a smooth, hardened steel face or a roughened face which may range from minor corrugations to tooth-like projections of solid steel as large or larger than building bricks.

One or both rolls of a roll crusher are normally held in position by means of heavy springs. These springs serve as safety releases in case a piece too hard for the crusher to handle or too large for it to pass is introduced into the rolls. Material makes one pass between the rolls and falls through without classification.

Cone Crushers. A rotary crusher resembling the gyratory is available for intermediate crushing. This crusher, known as a cone crusher, has a cone turning in a conical shell. The angle of taper of the cone is much greater than in the gyratory, however, and the cone pivots near the mid-point of its central shaft rather than from the upper end. This machine will give excellent service if the material is not too hard or abrasive. It is not comparable in production to the hammer mill or slugger roll, however, in the size range in which it operates.

Squirrel-cage Disintegrator. Another type of impact mill which has limited application is the squirrel-cage disintegrator. In this machine two rows of heavy bars are fastened near the edge of a circular plate and extend outward from the plate, parallel to the shaft; a second similar disk faces the first, its bars passing between those on the first. The two disks are rotated in opposite directions. Material fed into the mill will be broken up by successive impacts with the rotating bars.

Since the bars are rigid and unyielding, they will not last as long as those in the swing hammer mills where the hammers can swing back and pass over rock too hard to yield to the first hammer blow.

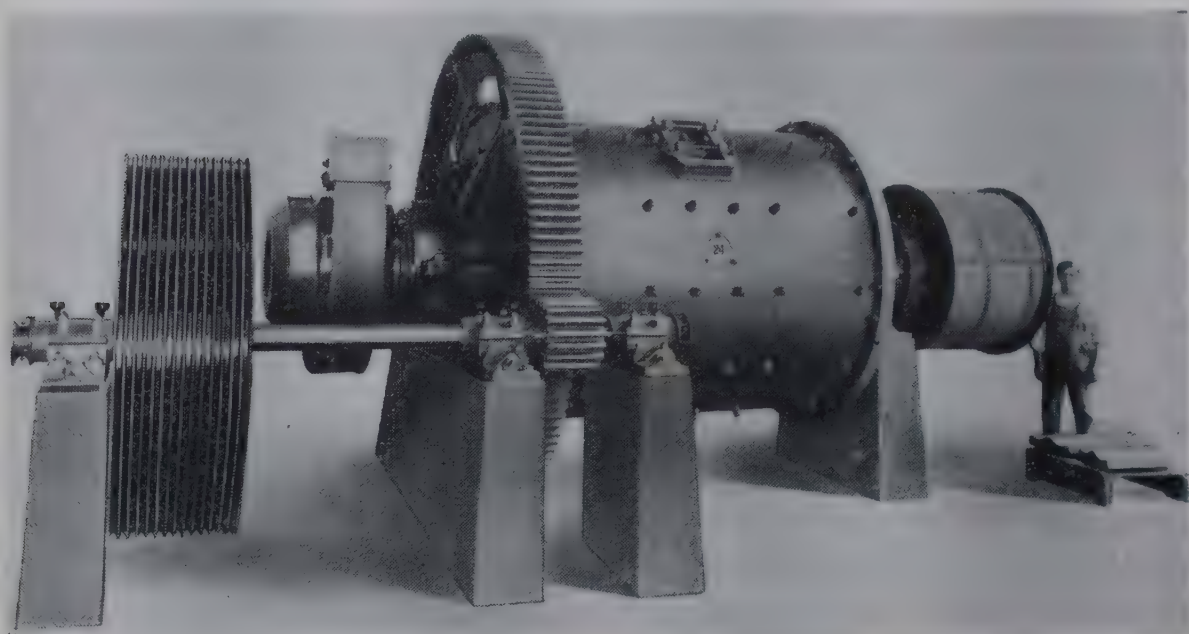
Disk Crusher. The disk crusher disintegrates materials between a stationary plate and a nutating disk. The stationary plate is saucer-shaped and has a hole near its center for the feed. The companion saucer-shaped plate faces the stationary plate, hollow side to hollow side.

Pulverizers

The fine grinding of rock involves problems not encountered in coarse crushing. One is the power requirement. Since the work required for reduction is roughly proportional to the increase in surface area, the per cent increase in power required is much greater per unit of weight when pulverizing than when crushing

to coarse particles. Another problem is concerned with the crushing action itself; in crushing large pieces the machines can take advantage of direct pressure, impact, beam action, and roll action. In pulverizing, attrition becomes very important, with limited possibility of using other types of crushing action except, perhaps, roll action.

Nevertheless, very effective machines have been developed for the fine grinding of rock. These differ from the ones designed for coarse grinding in that they must provide for close contact of



(Denver Equipment Co.)

Figure 38. Continuous Ball Mill. Scoop feeder at left.

grinding surfaces. The more efficient units have a positive means of removing the fine material, or removing both the fines and the coarse material, separating the two, and returning the coarser material to the mill.

Ball Mill. Probably the most widely used machine for fine grinding is the ball mill. It is used somewhere in virtually every industry where fine grinding on a large scale is a requirement.

The ball mill, in its basic form, is merely a steel drum arranged to be rotated on its axis, into which balls of steel, porcelain, flint, or granite are placed. The material to be pulverized is introduced and as the drum turns, the balls roll over one another, trap the material between them and pulverize it. The only major changes

in the basic design have been: (1) to make the machine continuous by providing a mechanism to feed it as it turns; (2) to remove finely ground material as it is produced; and (3) to make the machine more efficient by segregating the balls into zones by size.

The feeder of the ball mill may take any of several forms. A short scroll or screw conveyor is an effective means of feeding; or a convolute-shaped scoop which loads material into the mouth of the mill with each revolution may be used.

Discharge is effected by overflowing the crushed material out of a hole or grating at the center of the end opposite the feed, or by floating the ground material out in a stream of gas or liquid. In most cases the material is led to a size classifier and the oversize material returned to the mill. Since the gases or the liquids used for floating the material out of the mill in a fine-grinding circuit are freed of their suspended solids, there is no reason why they cannot be recycled to the grinder along with fresh feed. Consequently, gases other than air and liquids other than water often are used in fine-grinding cycles.

Segregation of the balls into sizes is accomplished in two ways. The Hardinge mill does this by the shape of the casing. Other mills have a cylindrical casing with the interior divided into sections by gratings, or divided by plates into sections as completely separated from one another as if they were a series of individual mills with the discharge from one forming the feed for the next.

Many ball mills have ribs projecting inward from the inside surface of the drum to prevent the balls from sliding. The ball mill is manufactured in a complete range of sizes from those used in the laboratory, which have a capacity of a few hundred cubic centimeters, to the giants used for large-scale commercial grinding. These are as large as 8 feet in diameter and 40 feet in length.

Rod Mill. The rod mill is structurally quite similar to the ball mill, except that hardened steel rods take the place of the balls. It will not usually grind as rapidly as the ball mill but it does deliver a much more uniform product.

Hammer Mills. Some hammer mills are made with small enough clearances to produce a relatively fine powder, the so-called "hinge hammer" type being able to make a product as fine as 1/100 inch in diameter.

Ring-roll Mills. If the hammers of a hammer mill are replaced by free rolling rings, the ring-roll grinder is obtained. Except for size, the general structure of this unit is quite similar to the hammer mill. However, the rolling rings which press against the housing as they move around the interior of the grinder gives a roll grinding action. In the usual pattern, the rings are alternated in each race, one ring having a smooth outside surface, the next one being studded. The studded roll agitates the material and the smooth one crushes it.

The ring-roll grinder may be discharged through a grid in the bottom like the hammer mill, which it resembles, or may discharge its product in an air stream.

Raymond Mill. Another rotary mill similar in action to the ring-roll mill, and equally popular, is the Raymond mill. The anvil of this mill is a circular steel ring laid on its side. The crushing rolls are swung as pendants from a cross-arm or spider mounted on a vertical shaft, and are held against the anvil by centrifugal force. Plows, also attached to the shaft, lift the material off the bottom of the mill and bring it up between the roll and the anvil. There is thus considerable agitation of the fine material and very effective crushing action results.

The Raymond mill is equipped with auxiliary equipment for removing the product by an air or gas stream. The product can thus be regulated to any degree of fineness required. This machine is extensively used for grinding coal for use in pulverized fuel boilers.

Sturtevant Ring-roll Mill. Another roll-type mill is the Sturtevant mill, in which the anvil ring is rotated in a vertical position, while the rollers are held against it by heavy springs. Closed-circuit grinding with the oversize being returned to the mill is normally employed.

Babcock and Wilcox Pulverizer. This mill is also designed for grinding by the action of a roll over a steel anvil. The grinding mechanism consists of a grooved ring which is turned rapidly between two ball-bearing races. Plows and discharge by air are similar in design and function to those of the Raymond mill.

Edge Runner. The edge runner is perhaps the oldest of all grinding machines. It is widely used today where its grinding and kneading characteristics can be combined to advantage, such as

grinding clay into oil to make putty, or mixing and grinding clays for use in the manufacture of ceramics. It is little used for grinding alone.

This machine consists of a heavy stone or metal roll (or pair of rolls) which is caused to roll over a flat bed by an axle or shaft attached to a cross-arm mounted on a vertical rotating shaft. The roll thus is moved over the bed, and since it is continually pulled toward the center by a circular motion of the shaft, it also slips continuously as it rolls. Plows move ahead of the roll or rolls and pile the material to be ground into their path.

Roll Pulverizer. The design of several machines is based upon attrition as the crushing action. The roll pulverizer is one of them. As compared to roll crushers, where the rolls are moved toward one another at the same speed, the rolls of the pulverizer are driven at different speeds so the solid to be ground is literally wiped through the slit between the rolls.

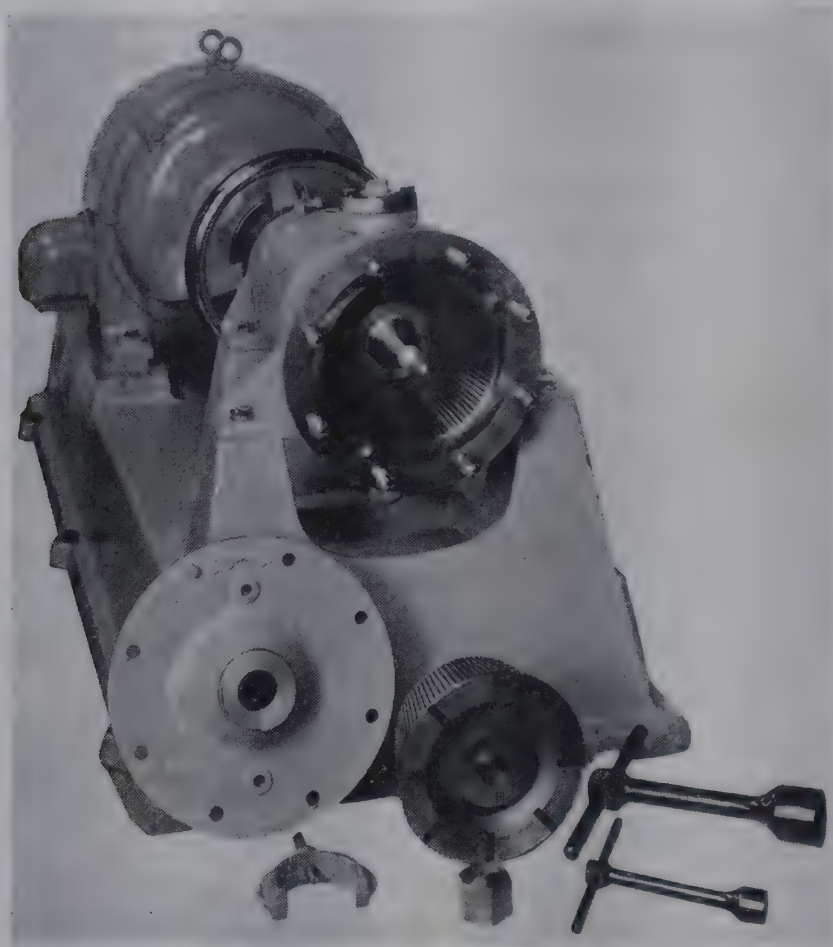
Roll pulverizers may be arranged vertically, with a series of rolls, one above the other, regrinding the solids with each pass. Guides pass the material from the discharge of one pair of rolls to the nip of the next pair.

Buhrstone Mill. The buhrstone mill, once a common device for fine grinding has for the most part given way to other grinding machines. Buhrstone mills are constructed of two flat stone disks set close together. These disks can be independently rotated at different speeds, or one can be held fixed while the other is rotated. The material to be ground is fed through a hole in the center of the upper disk, and works its way toward the periphery of the disks as they are turned. The material is thus wiped between the two faces of the disks and is ground in the process. The disks are usually roughened, or grooves are cut in the surface to assist in the crushing and to prevent the stones from overheating.

Coffee-type Mills, Cone Disintegrators, and Other Attrition Mills. Several other attrition mills have been built on the same principle as the buhrstone mill, but are normally made of steel, are capable of being driven at higher speeds, and have positive control of clearance setting to adjust the size of the product accurately. They are usually provided with better feed systems than the buhrstone mill.

The colloid mill, used to disperse solids in liquids, is an im-

portant member of this group. This is a reasonably high-speed unit having extremely close tolerances between the rotating element and anvil. The material ground in the colloid mill is always disintegrated in the presence of the liquid in which it is to be suspended. It is thus kept from overheating.



(Chemicolloid Laboratories, Inc.)

Figure 39. Colloid Mill, Standard Model. Dismantled to show grinding plug.

Jet Mills. Recent additions to the long list of grinders and pulverizers are the several patterns of jet mills. High-pressure steam or air is led into a circular grinding chamber through a series of jets arranged tangentially around the periphery of the chamber. The feed (smaller than $1/4$ inch) is injected into this chamber, where the intense agitation caused by the streams of steam or air entering the chamber cause the particles to bump violently against one another and against the walls of the chamber thus disintegrating them.

Flash Pulverizer. Another relatively recent addition to the

techniques for pulverizing certain friable materials is that of flash pulverization. A flash pulverizer is a unit in which reasonably fine and rather easily disintegrated material, such as coal, is entrained in highly super-heated high-pressure steam and then released through a nozzle into a region of lower pressure. The coal is broken into fine dust by abrasion of the particles in the areas of extreme turbulence as the steam is released through the nozzle, aided by the strains produced as the pressure in the particle is rapidly released.

Hand-grinding Devices. Devices such as the mortar and pestle, the buck board, on which material is crushed by a sledge, and the hand-operated drug mills are all important from a laboratory standpoint.

Reduction of Fibrous Materials

The size reduction of fibrous materials really taxes the ingenuity of the designer of grinding machinery. Many fibrous materials, such as rubber, rags, paper, plastic scrap, leather, wool, bark, and agricultural wastes such as straw, corn stalks, cane wastes, and similar materials, tend to resist the most determined efforts to reduce them in size—especially to a uniform size.

These materials will respond to mechanical treatment such as cutting, tearing, and threshing, and to some extent, rubbing. Cutting is by far the most useful method and would be ideal, were it not for the fact that some materials are not clean, and knives become dulled quickly. Dull knives or blunt threshers will give the tearing and threshing required for the disintegration of some materials, and attrition mills having rough or very rough surfaces may be used for the size reduction of others. Flash pulverizing and explosion techniques for disintegrating fibrous materials have solved these problems very effectively for several industries.

Many fibrous materials are given pretreatment, such as mild cooking, steaming under pressure, and similar operations to reduce the energy necessary for their disintegration, to soften them and thereby reduce wear on the knives, and to prevent brittleness which in the dry materials often causes excessive dusting during disintegration.

Mechanical Disintegrators for Fibrous Materials

Hammer Mill. The hammer mill used for the disintegration of fibrous materials may be either a cutter or thresher in character, depending on the sharpness of the knives.

Disintegration is usually accomplished by cutter bars or knives which extend outward like fingers from a rotating shaft, being held in position by centrifugal force. These knives are hinged near the shaft like the hammers of the more conventional hammer mill. A second set of knives or bars is fastened to the outer shell of the hammer mill and project inward from the casing. The knives on the rotor pass between the knives or bars attached to the casing and give a shearing cut to the material fed to the machine. Disintegrated material may pass through a grating or be blown out of the machine with air, or both.

These mills give excellent service in handling a wide variety of fibrous materials.

Rotary Knife Cutter. A number of machines have been developed to cut materials by a shearing action of a knife blade parallel to the rotating shaft. In these machines, knives are attached rigidly to a rotor, and fastened in such a way that the cutting edge is parallel to the rotor shaft instead of perpendicular to the shaft, as is the case of the hammer mill. These rotating knives are set to just clear bed knives which project a short distance from the casing of the cutter, with the sharp edges parallel to the shaft of the rotating element. Cutting takes place as the knives pass one another.

These machines are very effective cutters for a wide variety of fibrous material and are widely used. The machines are not particularly successful in handling waste paper, rags, or other material which fluffs appreciably as it is disintegrated.

Saw-tooth Disintegrators. Several patterns of disintegrators substitute saw teeth for either rotating or stationary knives. These are effective for reducing loose, pliable materials like rags where cutting, tearing, and threshing may all be necessary to open up the fiber properly.

Special Machines. Several large industries depend rather heavily on the production of either finely or coarsely divided solids

produced from soft or fibrous materials. These industries have developed machines which best fit their particular requirements. Since any one of these types of machines may handle millions of tons of material annually, they are probably more important than many of the more universal-type disintegrators.

The paper industry, for example, is concerned with the production of not less than three different types of disintegrated products from wood. One of these is chips, about the size of large buttons, for which a cutting machine called a chipper is used; a second is a coarse fiber, for which several machines, none too successful, have been developed; and a third is a fine material known as mechanical pulp, produced on a roughened stone and used for various grades of paper.

Beet sugar factories probably "slice" a quarter of a million tons of beets a day. The beet slicer is a cutter which produces a very particular type of disintegrated product.

Explosion Disintegration of Fibrous Materials. Many fibrous materials, if impregnated with high-pressure steam and then instantaneously released from the high-pressure chamber, will literally explode by the sudden release of the internal pressure which has been built up in the fiber bundles. This is the principle of operation of the highly successful "Masonite" process for converting waste wood stumps and roots from the lumber, pulp, and naval stores industries into a fiber suitable for forming into sheets. Although this process is currently used only in this particular industry, it is a novel and successful method of size reduction.

SIZE REDUCTION OF LIQUIDS

It would appear that the discussion of the size reduction of liquids might border slightly on the ridiculous since any kind of liquid spray gives small drops of liquid. Yet, for many processes, it is just as important to obtain large liquid surface areas per unit of weight as it is to achieve the same result for solids. Much effort has gone into the problem of producing spray nozzles or other equipment which will break up liquids of varying temperatures, viscosities, and densities into a fine mist or spray of uniformly sized droplets of liquid.

There are two general techniques available for breaking a liquid

into a spray. Several types of equipment are available under each of the general methods. The spray can be formed by flowing the liquid through nozzles with or without a blast of air or steam to assist the atomizing process, or by directing a stream of liquid against a rapidly rotating mechanical device. In addition, there is at least one method for distributing a liquid in fine droplets through a second liquid medium—the process of homogenization.

Nozzles

There are two classes of nozzles. One, known as a gas atomizing nozzle, uses air, gas, or steam to assist the operation. The second class, using no gas as an adjunct, is known as a pressure nozzle.

Pressure Nozzle. In the operation of the pressure nozzle, the liquid is brought into the nozzle at high pressure and reasonably high velocity. Here the liquid may do one of several things. It may be led through a channel and impinged on a surface where it is atomized; it may be broken into two streams which are directed at high velocity toward each other; or its speed may be greatly accelerated in the nozzle so that it leaves the nozzle at such high velocity that it is atomized on impact with the atmosphere.

Various styles of the first two types of pressure nozzles are classed as impact nozzles; they produce hollow cones, or fan or disk-shaped spray patterns. The impact nozzles, when operating properly, form quite uniform droplets.

The third style of pressure nozzle, in which the spray is formed by impact with air, is the most important. The various nozzles of the group are identified by the shape of the spray pattern as it leaves the tip of the nozzle. Thus there are fan nozzles, hollow-cone nozzles, and solid-cone nozzles, differing somewhat in construction but all embodying the same principle of spray production.

The selection of these nozzles depends entirely upon the spray pattern required. The hollow-cone pattern is quite satisfactory for most uses requiring a fine spray. The solid-cone pattern is useful for certain washing operations, for cooling, and for applications where complete coverage of a fixed area is required. The fan nozzle is frequently not too satisfactory, particularly in the

small sizes, for as much as half the liquid stream may be concentrated in the edges of the sheet, forming areas of considerably heavier coverage and carrying larger droplets than the remainder of the pattern.

Gas-atomizing Nozzles. In this class of nozzle the liquid is brought to the tip of the nozzle as a solid stream. At this point the liquid is caught by a rapidly moving gas stream where it is broken into a fine spray. The liquid may be forced to the nozzle by air pressure or by pumping, be conveyed to it by gravity, or be drawn through the feed tube by the aspirator action of the gas stream. The gas and liquid may mix inside the tip of the nozzle and emerge together, or may mix completely outside the nozzle proper.

Gas-atomizing nozzles can be set to produce an exceedingly fine spray. They can also handle more viscous liquids than the pressure-type nozzle. This operating advantage makes them favored for use in paint spraying and in oil burners using the heavier oils.

The gas-atomizing nozzle is generally available only in considerably smaller capacities than the pressure nozzle, and more power is required to deliver material through it.

Rotating-disk Spray

This spray, which physically throws the liquid in small droplets, is most useful in handling liquids so viscous that other nozzles cannot handle them, liquids carrying appreciable quantities of solids, or where widely varying quantities of material are to be discharged through one size of nozzle. The quantity of liquid can be controlled very easily by regulating the liquid inlet valve.

The liquid, under low pressure, is fed directly to the blades of the rotating-disk atomizers, or is drained into a cup from which the disk or vanes scoop the liquid as the blades rapidly revolve. If the speed is correct for the character of the material being sprayed, the liquid will be discharged from the rotor in a very fine spray.

For the most part, the rotating disk spray is not used where other spray or atomizing nozzles are satisfactory.

Homogenizer

The homogenizer, a machine for forming a very fine dispersion of one liquid in another, operates by forcing the two liquids together through an exceedingly small opening. The one liquid, for example fat in milk, is broken into very fine droplets and dispersed in semipermanent suspension in the other liquid.

SIZE REDUCTION OF GASES

Gas bubbles can be dispersed in a liquid to form a froth, which, in a manner of speaking, would represent the size reduction of a gas. This subject is considered later.

5 : SIZE CLASSIFICATION

Techniques of Size Classification

- Separation dependent on the dimension of the particle

- Separation by methods involving the ratio of surface area to mass

 - Selective settling (gravitational separation)

 - Hindered settling

 - Centrifugal (inertial) separation

- Separation involving the principle of free rolling over a surface

Size reduction, while important, is only one of two steps in the preparation of materials for reaction. The necessity of preparing materials of *uniform* size is fully as important as size *reduction*; this, the second step, is called size classification. Since solid materials are the only ones which, when dispersed, will respond readily to classification processes, the descriptive material in this chapter is limited to materials in the solid state.

The products of many chemical reactions involving solid materials may be seriously damaged in quality and appreciably lowered in yield if the reaction does not go to completion, or if the products and reactants are allowed to remain in contact after the primary reaction has been completed, and undesired secondary reactions are permitted to occur. Consequently, for many reactions, it is necessary that all particles be of similar size so that reactions can go to completion with a minimum production of unreacted cores and products of side or secondary reactions.

Very fine particles of a material may also have deleterious effects in a reaction mass other than directly harming the quality of the product. They may consume reacting chemicals without producing any usable end products. The presence of the fines may create difficulties in circulating reacting liquids or gases through the solids. They may increase difficulties of removal from gaseous products or complicate operations of purification after the re-

action is completed. To prevent loss and difficulty from unreacted cores the oversized material should be separated. The fines should be removed for any or all of the several reasons indicated.

In grinding operations, particularly fine-grinding, it is important that material of the size required be removed as rapidly as possible from the grinding machine to avoid regrinding acceptable material and its loss as fines, and to increase capacity and lower power consumption of the grinding equipment. This can be achieved either by removing the finely ground material in a carefully regulated stream of air, or by blowing, washing, or otherwise removing all the material from the grinder, passing it through sizing equipment, and returning the oversize to the grinder for further treatment.

The following factors govern the final choice of a classification technique.

1. Accuracy required
2. Number of sizes in which material is to be separated
3. Necessity for changing sizes (versatility)
4. Fragility of the material being sized
5. Condition of the material, such as
 - a. Wet
 - b. Dry
 - c. Fluffy
6. Shape of the individual particles
 - a. Actual shape
 - b. Uniformity of shape
7. Size of the material to be classified
8. Quantities involved
9. Whether or not the material can be suspended in a gas or in liquid without harm
10. Density of material to be classified

TECHNIQUES OF SIZE CLASSIFICATION

The most accurate method of sizing solids is by separating large from small particles on the basis of differences of dimensions in an operation known as screening. Particles above a certain size

are separated from those smaller in size because the smaller ones will pass an opening which will hold back the larger ones.

A second technique for size classification is based on the fact that a large particle of the same density as a small one has less exposed surface per unit of weight and will therefore be less affected by its surface as it passes through a gaseous or liquid medium. Put more simply, a large particle will settle more rapidly if dropped in a fluid (gas or liquid); it will travel farther horizontally in a fluid if given an equal initial horizontal velocity; it will be lifted with greater difficulty, and carried a shorter distance by a stream of air, and dropped more quickly if the air stream is suddenly reduced in velocity; or if acted upon by centrifugal force in an air stream it will be thrown out of the stream with greater ease than will the smaller particle.

A third technique is based on the fact that a large particle is less impeded in its travel down an inclined roughened surface than is a small particle.

Commercial equipment making use of each of the principles of separation of materials into size ranges is manufactured.

Separation Dependent upon the Dimension of the Particle

Screens. It is normal to separate various sizes of solids by screening if possible; only if this fails, or if the accuracy obtainable in this way is not required, is it necessary to consider other methods. Screening may not be too successful if the material is relatively fragile; if all of it is very small, or especially if it is both small and highly irregular in shape; if it is wet—(unless it can be washed through the screen); if it is sticky or fluffy (like cotton linters, for example); or if it is very odd-shaped, having for example, extremely small dimensions in one direction compared with average or large dimensions in the other. In these cases other techniques are advisable.

There are several terms in connection with screening operations which should be defined briefly. Screening accuracy is an indication of the amount of fine material which does not pass a screen coarse enough for it to drop through. Capacity usually means the volume or weight of material passed per unit of area of the screen surface in a given time. Blinding is that property of irregularly

shaped particles, or of particles which are slightly too large to pass the screen to lodge themselves in the openings. Some materials may cause such serious blinding of screens that sizing of those materials becomes difficult if not impossible.

Screening equipment, both parts and complete assemblies, is manufactured by a number of firms. Since each attempts to meet competition, it is not surprising that there is such a large variety of screens available. As major divisions, there are rotary screens and flat screens; the latter may be vertical, inclined, or horizontal, and may be stationary, traveling, shaking, or vibrating. Screens may be arranged to operate on dry materials or on materials suspended in a liquid.

Screens have two major parts: the screen surface, and the mechanisms for presenting fresh material to the screen surface and for moving the oversize off the screen. Auxiliaries, such as positive means of moving material through the screens, and devices to dislodge blinding particles, reduce dusting, regulate feed, and remove products are often provided.

Screen Surfaces. Screen surfaces may be parallel bars (grizzly); perforated plates made by cutting, punching, or milling openings in metal plates; or woven wire or cloth stretched over a frame.

The bars of the grizzly are seldom set less than one inch apart, and are normally spaced at intervals of several inches.

The holes in plates, either round or rectangular, are formed in sizes from about $1/8$ inch to perhaps 4 inches in width or diameter. It is only in slotted screens that perforations are very fine. These may be milled down to widths of 0.005 inch or less. The spacing and geometric pattern of the holes in screens must be specified. Closer spacing gives greater operating area per unit of screen area, but a structurally weaker screen.

Wire screen is made in sizes having openings about 4 inches on a side down to a gauze with 400 openings per linear inch, in which, in a standard wire screen, the openings have a dimension of 0.0015 inch on a side. In sizes above $1/4$ inch, the opening is specified by the actual dimension of the opening, as for example $1/2$ inch, 2 inch, etc. The opening size, in screens smaller than $1/4$ inch, is indicated by the term "mesh," or number of openings per linear inch.

Mechanical Operation. The mechanical operation of a screen has three objectives: (1) to promote the continuous presentation of unscreened material to the screen surface, (2) to assist the undersize particles to pass through the screen openings, and (3) to free the screen surfaces of particles which clog or blind the openings. That operation which will promote all three of these objectives simultaneously, at the minimum cost for power, purchase and installation, operation, maintenance, and with the least vibration and other operating difficulties, is the most appropriate one to use.

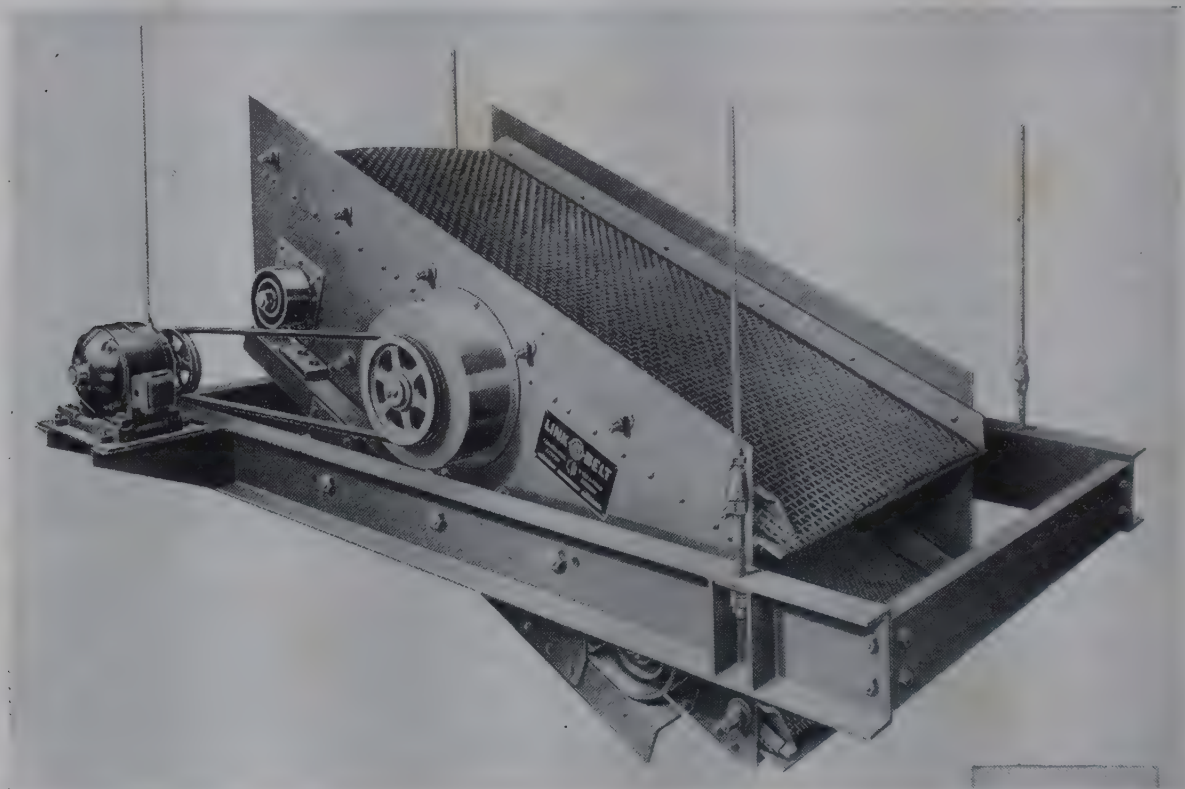
There are several methods of operating screens. Some screens are stationary, but most are movable. In the latter group the screen may move continuously, as in a conveyor; or oscillate, shake, or vibrate; or rotate. The majority of screens operate in an inclined position, the angle of inclination ranging from 10 degrees from the horizontal to as much as 60 degrees. Usually, the greater the angle of inclination, the less accurate is the separation, because of the greater tendency of particles small enough to pass through the screen openings to roll and bounce over them rather than to pass through them.

There are a number of screens in operation in which the bulk of the material drops through the screen without resistance, and only an occasional particle, rock, or lump is too large to pass. Mechanically induced motion of the screen surface in these cases is unnecessary.

Shaking Screens. Shaking screens, in which the screen surface is moved rapidly in a plane more or less parallel to the screen surface, are available commercially in a variety of patterns. The motion may be gyrating, reciprocating, or oscillating, or combinations of these.

The shaking screen has two general operating advantages: (1) the material tends to stay close to the screen surface, and (2) the shaking action tends to segregate the finer particles in the lower portions of the layer of material on the screen. Mechanical devices are often needed to relieve the tendency of this screen to blind. The reciprocating shake of a screen weighing only a few hundred pounds may be enough to discourage its use. Vibration and wear on moving parts is excessive. Therefore, gyrating or combination shaking devices are far more favorably received.

Vibrating Screens. Vibrating screens, in which the motion of the screen surface is in a direction roughly perpendicular to the screen surface, have become the most popular type for coarser materials. Their motion is somewhat violent, which may cause dusting. For this reason, they are not as practical in many cases for fine screening as is the shaking screen. However, their capacities are usually larger and screening is likely to be more accurate



(Link-Belt Co.)

Figure 40. Vibrating Screen. Weighted flywheel; suspension mounting.

than that obtained by the shaking screen. They require little or no extra effort to keep them relatively free of blinding.

Vibrating mechanisms are of two types: one which moves the entire screen frame, and one which moves only the screen surface. Both are used extensively. The vibration of the entire frame necessitates heavier construction but gives the same "throw" (amplitude of reciprocating motion) over the whole screen surface. Movement of the screen surface only requires less power and is less noisy. However, the screen has a variable throw, which is a maximum near the center where the vibrating mechanism is

attached, diminishing to zero where the screen is fastened to the frame.

The gyratory or shaking screens are somewhat superior for screening light, bulky, dusty, or very fine materials, and the vibrating screen is best adapted to handling heavy or large particles.

Horizontal Screens. Horizontal screens have no means of removing oversize material by gravity alone. However, if only an occasional oversized lump is encountered, it can be removed by hand. There is some advantage in the larger capacity, easier construction, and greater space or headroom with the horizontal arrangement. Usually it is necessary to employ some positive means for discharging the oversize. Several screens do have such devices.

Revolving Screens. In the revolving screen the screen surface is supported around a cylindrical shell. In the simplest form, the material is charged through a spout into the open end of the cylinder and tumbled over and over until the fine material is discharged through the screen surface. The cylinder is tilted slightly from the horizontal so that the oversize works down inside the screen and can be withdrawn from the lower end.

The most advanced designs of revolving screens are marked by improvements in drive, feed devices, and the fastening of the screen surfaces, and by the addition of various sized screens and accessory devices to give more than one size separation simultaneously.

Compared with flat screens in general, rotating screens are much quieter; they have a motion which does not cause vibration difficulties in the structure; they have a high capacity per single unit; and since the screen is turned over with each revolution, blinding is not serious. However, they have a large screen surface which is not in use, and therefore, are not as efficient; they are rather rough on the material to be screened since it rolls it over and over in the unit; and most serious of all for general purposes, they do not give good classification simultaneously into several size ranges, and cannot be changed readily from one size classification to another. •

Separation by Methods Involving the Ratio of Surface Area to Mass

Solid material, fine enough to be floated or carried by a stream of gas or liquid but still heavy enough to settle if allowed to remain in a quiescent state, presents good possibilities for separation into size ranges. Moreover, separations which make use of this property often can be accomplished at a fraction of the cost of the screening operations. The accuracy of separation is sometimes not as good as that obtained with the screen, but with the latest improvements, claims are made for accuracies which are quite remarkable.

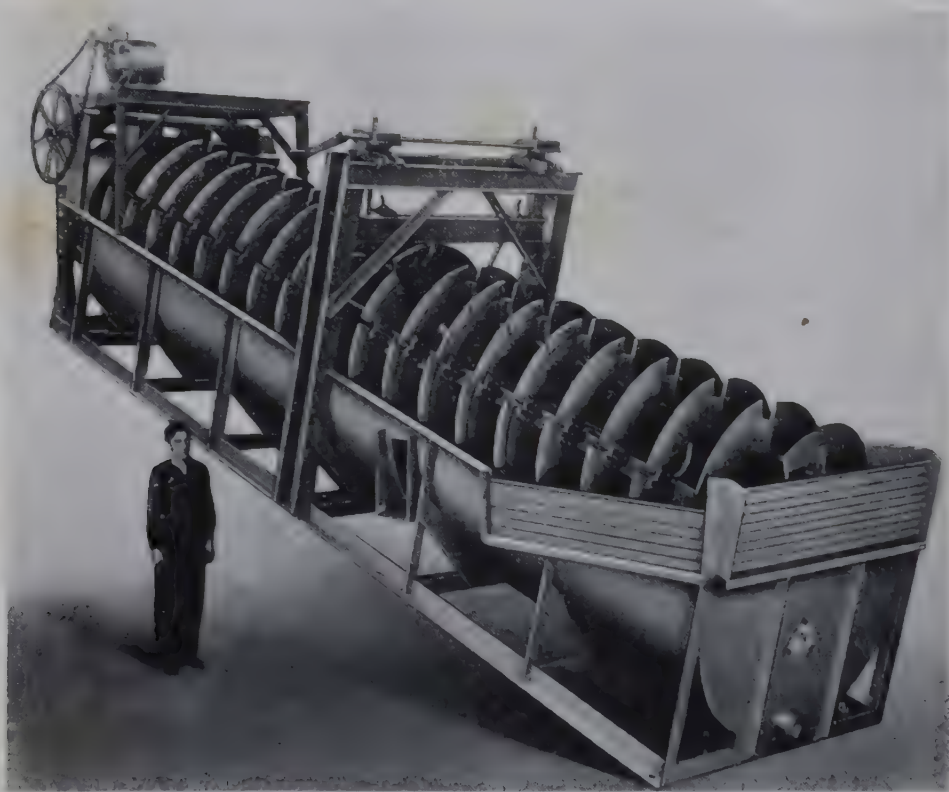
Selective Settling (Gravitational Separation). While it is entirely possible to settle selectively small particles in a gaseous medium, other methods are more satisfactory; the technique of selective settling is usually limited, on a practical scale at least, to settling solids out of liquid media. In this technique the solid mixture, suspended in a stream of the liquid, is directed by the stream into some type of equipment which has a reasonably large volume and in which the speed of liquid flow is greatly reduced. The heavier solid particles are settled out, while the lighter ones leave with the liquid in the overflow.

Classifiers. The most widely used equipment, of the several kinds available for this purpose, are the classifiers. All are similar in that they provide a settling basin, an overflow for the water carrying the finer particles, and some positive means of removing the heavier particles which settle out. Major points of distinction between the classifiers relate to the method of withdrawing the settled solid. Drags or flight conveyors, screw conveyors, movable rakes, and internal scrolls are used in the various patterns.

Decanters. When a mixture of solids and liquid contain a relatively small portion of solids which are to be settled, some form of decanter may be suitable. The decanter is a tank—usually a relatively small one—in which the liquid may be held quiescent long enough for the grains of material to settle. The tank is usually fitted with a conical bottom, or it may be built in the shape of a cone to concentrate the settled solids so they can be easily withdrawn by gravity through the bottom. By arranging

several decanters of increasing size in series, a rough separation of solids into sizes can be achieved. The retention time in each decanter being somewhat longer than the one before it, progressively finer material will tend to settle in each.

Thickeners. The thickener has a very large volume, and as a consequence, a relatively very small liquid velocity through it. Although normally of more interest in liquid clarification, it can



(Denver Equipment Co.)

Figure 41. Classifier. Akins type.

be used, usually in the smaller sizes, for the separation of finely divided, slow-settling solids from those which are colloidal or semi-colloidal in nature, and which settle extremely slowly, if at all.

The thickener is a large tank into which the solids and liquids are introduced in such a manner as to cause as little turbulence as possible. The coarser solids slowly settle to the bottom where they are continuously and slowly raked toward the center where they are flushed out. The liquid plus the unsettled solids overflow into a collection channel or launder at the rim of the tank.

Hindered Settling. If slight or sometimes quite energetic agitation is given the suspending media, the settling of finer

particles may be hindered to such an extent that heavier particles will pass through the suspension and will be deposited in layers roughly indicative of their size. At least two techniques for accomplishing this type of size separation have been developed, both of which are in only limited commercial use.

The mineral jig, a commercial unit for application of hindered settling, is used almost exclusively for the separation of light granules from heavy ones of approximately the same size.

The technique known as *elutriation* achieves size separation by passing solid particles downward against a stream of liquid or gas traveling upward through the apparatus. This technique is used for the laboratory scale separation of very fine powders.

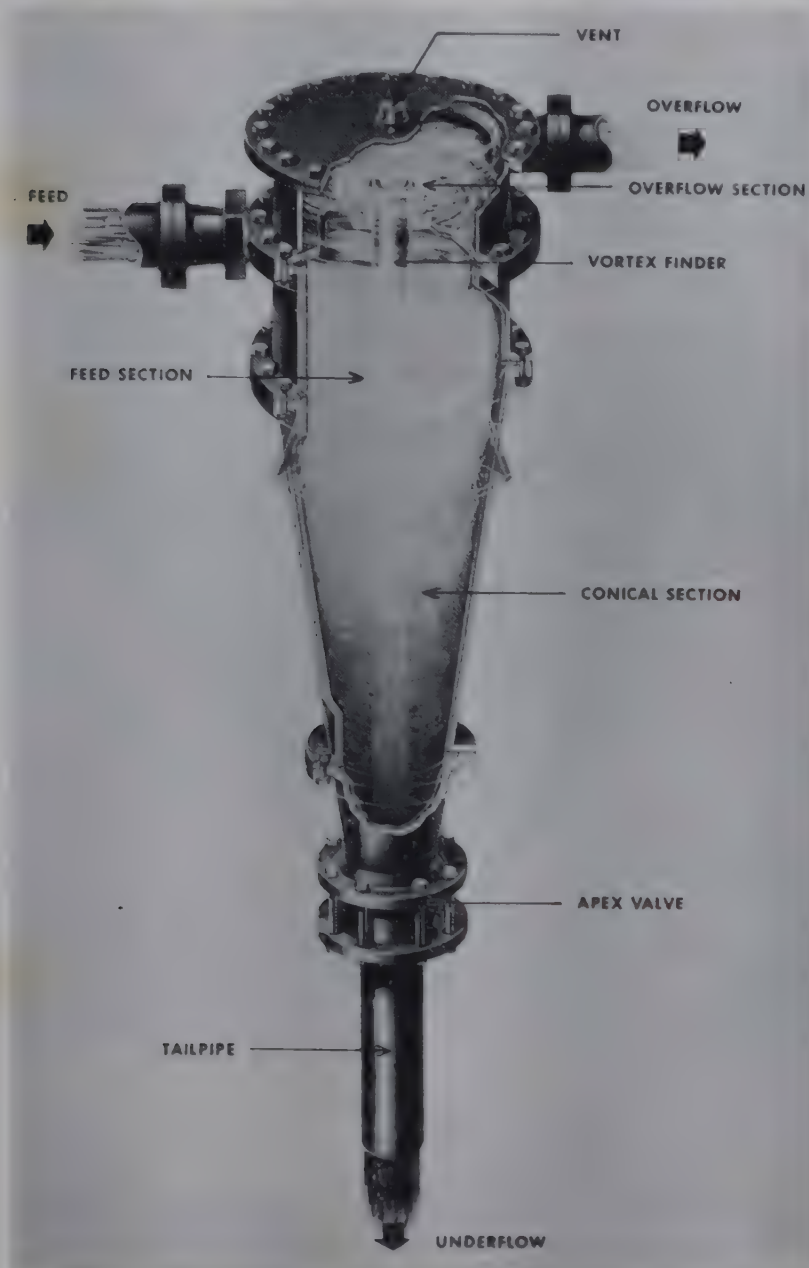
Centrifugal (Inertial) Separation. If solid material is held in suspension in either a gas or a liquid, and if the suspension is caused to rotate rapidly around a guide, the solid material will be thrown out by centrifugal force; the finer or lighter the particle, the faster the rotation must be to effect removal by this means. Consequently, by changing the diameter of the unit, or the velocity of stream flow, size separation can be obtained.

Air separation is most important, and there are many makes of such equipment. These units all have the same basic design and vary only in detail. In some types the motion of the gas through the unit is induced entirely by the inlet velocity; in others the speed is greatly increased by a centrifugal fan located in the separator in such a fashion as to whirl the gas within the separation chamber.

In the separator without a fan, the gas must be introduced at a high speed tangentially into a cylindrical chamber. In this chamber it is given a whirling motion which it retains as it passes on down the cylinder. Under the cylindrical chamber, and joined to it, is a conical section through which the gas passes, depositing solids as it whirls. The gas then leaves upward through a central tube which projects from the top downward into the cone. The solid material thrown against the conical walls slides down to the apex of the cone, where it is withdrawn.

The separator equipped with internal fans simply uses the fans in the cylindrical section to increase the rotational speed of the gases. The solids are discharged in the conventional manner down

the sides of the discharge cone. The blower section may be also located in a vertical position, the settled particles being held on the wall by the centrifugal force of the moving air stream. The



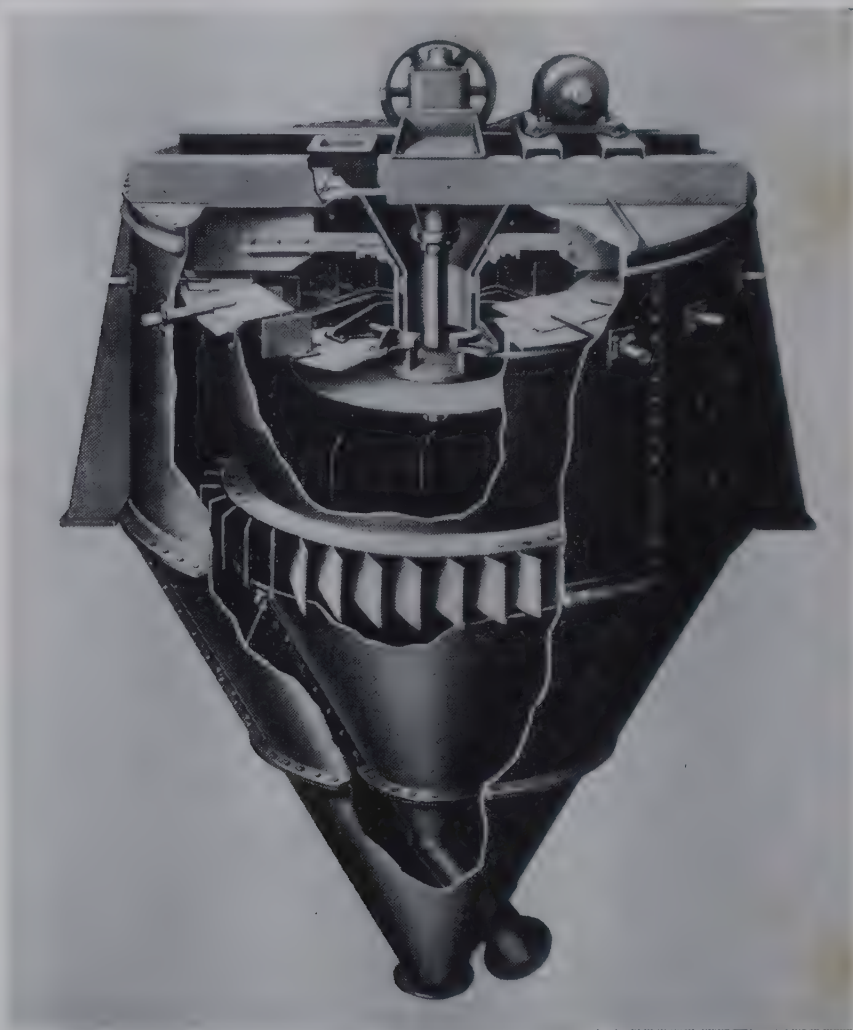
(Dorr Co.)

Figure 42. Cyclone Dry Classifier (Dorrclone—Dutch State Mines Cyclone).

solid particles are then skimmed off the sides by mechanical devices.

Separators are available in which a liquid may be substituted for the gas. For some reason, however, these have not been as popular for size separation of solids as are the air separators. The principle of centrifugal separation of solids from liquids is

extensively used, and this will be discussed in the appropriate section.



(Sturtevant Mill Co.)

Figure 43. Centrifugal Dust Separator, mechanically driven.

Separation Involving the Principle of Free Rolling over a Surface

As previously stated, a large round particle will roll more easily over a roughened surface than a small one of equal density. This principle is the basis for several separation techniques of considerable interest. The methods in use are given the general descriptive name of "tabling." The separation can be carried out on a wet table, a dry table, or a so-called spiral concentrator.

Wet Table. The wet table which is used today is not essentially different from the one developed by Wilfley over a half century ago. It consists of an elongated table, over the top of

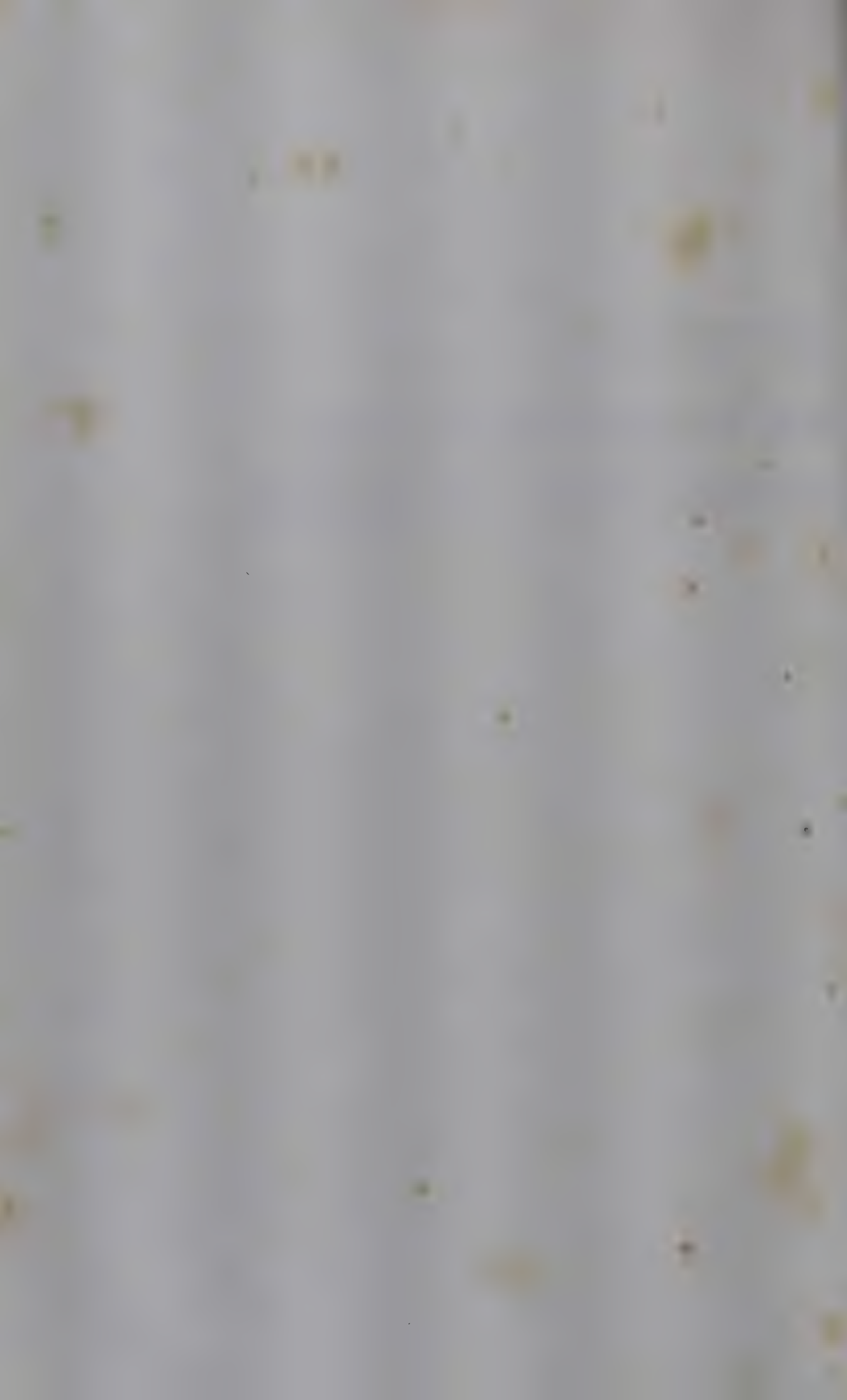
which is attached a series of strips or other devices to provide a riffle-like surface. The table is inclined slightly from the horizontal, and is shaken, rapidly in one direction and more slowly in the reverse. The material, in water suspension, is introduced at the upper edge of the table and flows down across the riffles. The coarser particles, which are less affected by the obstructions, are swept in the water stream while the fine particles which are caught by the riffles are moved slowly along them by the reciprocating motion of the table, and are finally discharged at or near one end of the surface.

Dry Tables. The dry tabling operation is not essentially different from the wet, except that larger lumps can be successfully tabled dry. The dry table has certain advantages when the material cannot be wetted, or where water costs make wet tabling prohibitive.

Spiral Concentrators. The spiral concentrator is a rather recent addition to the list of equipment designed for the separation of materials by size. It is a channel of curved cross section arranged as a helical chute. The material, suspended in a liquid medium, is introduced at the top of the spiral and the double eddy currents formed as the liquid runs through the trough cause the small particles to seek the inside of the spiral while the larger ones are carried in the liquid to the outside.

SECTION III

THE PRODUCTION AND DISTRIBUTION OF ENERGY



6 : ENERGY SOURCES

Commercial Energy Sources

- Solar energy
- Hydraulic energy
- Electrical energy
- Chemical energy
 - Solid fuels
 - Liquid fuels
 - Gaseous fuels

There are few chemical reactions which do not require the addition or removal of heat or energy. This is necessary in order to maintain the temperature at such a level as to promote high reaction speed without deterioration of products, or to develop maximum yields. Physical operations, such as mixing and the solution of materials, may develop heat which must be dissipated; still others, such as the reduction of viscosity or the acceleration of solution, may require the addition of heat. The various techniques involved in the production and use of energy are, therefore, highly important.

In spite of the fact that many scientists have been employed for several years and billions of dollars have been spent on research and development relating to the use of the energy of nuclear disintegration, the production of energy from this source economically and technologically suitable for industrial application is not currently possible. Solar energy, probably derived from nuclear disintegration, is the source of most of our familiar stores of energy. The gravitational energy of the moon and the rotational energy of the earth should not be ignored, although little direct industrial use is made of them. Finally, there are several types of energy which are suitable for direct use or for conversion to heat or mechanical energy. These are the hydraulic

energy of moving fluids, electrical energy, electrochemical energy, and most important, the chemical energy stored in fuels.

The selection of the proper source of energy for use in chemical reactions or related operations involves the following factors:

1. The temperature (heat level) required
2. Cost of purchase and use
3. Uniformity of source
4. Continuity of supply
5. Amounts required, and ease of transmission
6. Ease of conversion to other types of energy, especially high level heat energy
7. Cleanliness in handling, storage, and use
8. Safety in handling, storage, and use
9. Possible contamination of reaction mass
10. Heating or energy value per unit of weight or of volume
11. Labor involved in handling and use
12. Possible deterioration while in storage
13. Toxicity of materials or of end products.

COMMERCIAL ENERGY SOURCES

Solar Energy

Solar energy, important as a fundamental source of energy, has little direct industrial use. Its one advantage is that it costs nothing to produce, although the cost of collecting it may be appreciable. There are many other disadvantages. It is a widely fluctuating source, varying between a maximum and virtual zero every twenty-four hour period. There is little energy available on cloudy days, and it varies in intensity from season to season. It is of such low quality (low temperature difference between the maximum which can be produced and that of the heat absorbing medium) that large areas must be exposed to cause substantial amounts of heat to be transferred.

Even with all these disadvantages, solar energy is sometimes used as a source of heat, notably in the concentration of natural salt brines.

Hydraulic Energy

Large quantities of hydraulic energy are available almost everywhere in the natural movement of liquids and gases. Some

of this energy is relatively easy to convert to mechanical and electrical forms.

Rivers. The major sources of hydraulic energy are streams and rivers. Many streams are located in areas where their level can be artificially raised by dams and their water impounded in the lakes which are formed. As water is led from these lakes through conduits (penstocks) to water-driven turbines located at lower levels, the potential head of the water in the lake is converted first to velocity head, and then to mechanical energy.

Since most storms move in a general west-to-east direction, and since moisture is more likely to be precipitated as the cloud masses are pushed upward by mountainous terrain, the western slopes of the Pacific Coast ranges, of the Rocky Mountains, and of the Appalachian chains get the largest rain- and snowfalls; the rivers draining these areas have the largest and most uniform water runoff of most American rivers. Consequently, many of the major power projects are located on streams draining these areas.

Uniform supply is an essential part of satisfactory power production, and while the use of the large storage reservoirs does much to level out the supply of water, there is always the possibility of drouth, which will materially reduce water supplies and hence cut down the rate of power production. The construction and maintenance of standby steam plants is therefore often necessary to assure adequate and uniform power supplies. This is expensive and frequently discourages extensive development of water-power projects.

Most hydraulic machinery, and steam turbines as well, cannot function properly except at their optimum operating conditions, and they cannot be very easily turned on and off to meet peak power demands. Consequently, virtually all commercial producers of electric power have generating capacity well in excess of requirements during the latter part of the night. During this period power is exceedingly cheap, and some plants which have large power requirements are designed to be operated during this low-cost power period.

Tides. In spite of much investigational work that has been done, only a few projects have been even moderately successful in harnessing the power in the tides. These receive water at high

tide and release it through low-head turbines at low tide, or allow the water to run through turbines into the trap at high tide, or both. These methods are of some interest where exceedingly high tides exist, and where there are fairly large natural bays which have mouths narrow enough to dam at reasonable cost.

The chief difficulty with the tide trap is the fluctuating quantity of power obtained; about half the time no power at all is produced. One solution of this problem would be to develop power as water flows in both directions, but even with this arrangement the power produced would reach zero at certain periods of each cycle.

Wind. There are parts of the world in which the wind blows with sufficient velocity to make wind power practicable. However, because of the irregularity of wind velocities, power developed from this source is far too erratic to be useful commercially. Wind-driven mills find minor application in remote and windy locations.

Electrical Energy

While natural electrical discharges may be rampant during an electrical storm, there are no methods available for converting natural electrical energy to a form suitable for commercial use. All electrical energy used in present installations is generated from mechanical energy developed in turn from some other source.

Electrical energy has many advantages: it can be converted to chemical energy, heat, or to mechanical energy with almost equal ease. It can be transmitted with little loss over great distances. It is clean, and it can be closely controlled. It can be used to produce the highest industrial temperatures, and since the production of heat is not dependent upon any chemical action, the atmosphere of the heated system can be controlled readily. Its one disadvantage is its high cost.

Chemical Energy

Chemical energy, stored in the ground in the form of solid, liquid, or gaseous fuels, is the energy of greatest importance to

the present-day industrial world. Not less than 95 per cent of all energy produced and used comes from sources which are strictly chemical in nature.

Chemical energy may be used in several ways. It may be passed directly from one system to another; it may be converted to heat, and that heat passed directly to an absorbing reaction; it may be converted to heat which is used to produce steam, and the heat contained in the steam absorbed by the system requiring the energy; it may produce steam, which in turn produces mechanical energy; the mechanical energy may be converted to electrical energy, which is used directly or for the production of heat or mechanical energy, as circumstances may direct.

Fuels have come to mean carbon and hydrogen and various combinations of these elements, with varying amounts of oxygen, free water, and a number of inorganic impurities. The calorific or heating values of fuels are derived almost entirely from the carbon and hydrogen. Oxygen, when present, indicates a pre-oxidation of combustible material and its presence not only dilutes the fuel by the amount of its percentage, but also removes carbon or hydrogen from availability for further reaction. Sulfur, which is nearly always present in natural fuels, is definitely harmful, especially in large percentages.

A solid ash is nearly always a residue of the combustion of solid fuels. Its removal from furnace grates adds to the expense of operation. Depending upon its character, the ash may also cause operating difficulties in making clinkers in the fuel bed, and in spreading fly ash throughout the furnace system and on the area around the plant. There are also several sources of heat loss in the ash.

The free water in the fuel is a diluent, and like the ash, consumes certain amounts of heat which are lost to the system. The presence of water in a liquid fuel may cause operating difficulties such as frozen fuel lines. Moisture may cause solid fuels to fracture as they dry.

The primary item to be considered in the selection of an industrial fuel is its cost, although several others are also of importance. Availability, convenience, continuity of supply, uniformity, ease of combustion control, freedom from ash, concen-

tration (heating value per pound), freedom from smoke and from deleterious substances in the combustion gases, ease of moving fuel to the burners, and problems of storage must be considered in the final selection of the fuel most appropriate for any particular use.

Fuels may be classified into three groups according to their physical state—solid, liquid, or gas—and into two classes, depending on whether they are natural fuels (used without or with only minor upgrading) or manufactured fuels, either synthetic, by-product, or processed natural fuels.

Solid Fuels

Natural

The natural solid fuels account for the major portion of the total energy value of all fuels used. It is thought that solid fuels, and possibly liquid fuels as well, are derived from fossil vegetable matter. They were probably all derived from the carbohydrates $[C_x(H_2O)_y]$, and solid fuels generally improve in grade as the fuel molecule contains less oxygen.

Wood, which has the general formula $(C_6H_{10}O_5)_x$, has a carbon-hydrogen-oxygen ratio of approximately 50:6.2:44 by weight. Its calorific value is low, from 5,400–7,800 Btu per pound, oak having the lowest and pine the highest value. Green wood is so nearly saturated with water that it takes a large amount of heat to vaporize the water. Even thoroughly air-dried wood will normally contain from 10 to 20 per cent moisture.

Wood has some interest in heating operations because of its cleanliness and freedom from ash. However, except where it is available as scrap, and where other fuels are not readily accessible, it is seldom used as a commercial fuel.

Peat. In many parts of the world, there exists a brownish or brownish-black fuel called peat. It is probably in the first stage in the conversion of vegetable matter to coal. Brown peat has a carbon-hydrogen-oxygen ratio of 50:6.2:42 and black peat, 60:5.3:32. Thus it is apparent that the oxygen is being ejected slowly from the original carbohydrate molecules. The heating value of peat varies from 7,800 to 11,500 Btu per pound.

The main objection to peat is its high moisture content, which may reach as much as 90 per cent. The heat required to vaporize this water may be in excess of that obtained in its combustion. Peat dries readily, however. The first of the water is generally pressed out; additional amounts are removed by air-drying and the last (to about 10 per cent residual) is removed by heating at 150°F. The porous material remaining may be compacted by pressure. Peat has little industrial value.

A fuel known as *lignite*, darker than peat, containing a higher percentage of carbon, and a lower percentage (35 per cent) of water, exists in large tonnages in various parts of the world. Its heating value is high (11,500 to 14,000 Btu per pound). It would be a much more important fuel were it not for the fact that it becomes quite fragile as it dries. Consequently it is difficult to ship, store, and use.

Bituminous coal, which has the widest range of composition, occurrence, and use of any of the solid fuels, is thought to be the next stage after lignite in the gradual transition of vegetable matter to almost pure carbon. The heating values range up to 16,000 Btu per pound. Bituminous coal exists in almost all parts of the United States.

There are fundamental differences in various kinds of bituminous coals, the most marked being the action of the coal when heated. Some coals fuse together when heated to form hard lumps of carbon and ash (coke), while others either change little or eventually break apart to form a dust. Some bituminous coals take up oxygen quite readily to set up conditions leading to the possibility of spontaneous combustion. These coals are especially difficult to store because of their marked tendency for self-ignition. Bituminous coals are also quite serious offenders in the production of smoke. The widespread use of mechanical stokers has largely eliminated any differences in desirability of coals from this standpoint.

Anthracite. In the transformation of vegetable matter to pure carbon, the final coal stage is anthracite. It contains the highest "fixed" carbon percentage of any coal. Its occurrence is rather limited, and its use, once extensive in the metallurgical industries, has been sharply reduced by the substitution of coke. The heat-

ing value of anthracite is seldom more than 15,000 Btu per pound, and is thus somewhat less than certain varieties of bituminous coal.

Manufactured Solid Fuels

There are two general varieties of manufactured solid fuels: those in which the chemical nature is altered, such as charcoal and coke; and those in which, like briquettes and powdered fuel, most of the change has been wrought in the physical appearance or properties.

Charcoal, once quite important but now almost entirely replaced as a fuel by coke, is made by the destructive distillation of wood. The charcoal retains the general shape of the original wood, shrinking somewhat in the process and turning to a black, light, porous solid.

Charcoal is produced in closed and externally heated retorts, the volatile material being driven off and collected. This volatile material contains methanol, acetone, acetic acid, and other so-called wood chemicals, and, for years, was the chief source of these chemicals. With the successful synthesis of most of these chemicals the char alone must bear the cost of its production. Consequently charcoal is expensive, and its use as a fuel is therefore extremely limited.

Coke, composed chiefly of carbon and the ash-forming constituents of coal, is formed by the destructive distillation of coal. The retorts most used for the coking operation are slender chambers located in groups similar to the slices in a loaf of sliced bread. They are from 12 to 20 inches thick, 6 to 20 feet high, and 30 to 45 feet long. Ten or more tons of coal are coked in each chamber daily.

The chief use of coke in industry is in blast furnaces. For this use it must be porous to provide proper reaction conditions, and hard and strong enough to sustain the weight of the charge. Coke burns without smoke. It is, however, somewhat more expensive than coal.

The economics of coke production has gone through a rather interesting series of fluctuations. Early coke production was largely as a by-product of gas manufacture, the coke made was

poor in quality, and there was little use for it. Charcoal, and then anthracite, was used for steel production. As research improved processes, coke of higher quality was made, and this material slowly took over the markets for charcoal and anthracite. Coke then became the major product, with the gas a profitable by-product. The tar by-products, including ammonia, were important chemicals. Their production was controlled by coke and gas production, and there was no other good source for many of them. With the advent of cheap synthetic ammonia, the wide extension of natural gas lines, and the successful low-cost syntheses of many of the tar chemicals, the market for some of the by-products of coke is much more limited than it was. Coke itself must again, like charcoal, bear most of the expense of its production.

Lignite, peat, any coal, or even wood may be powdered, mixed with tar or other adhesives and molded into *briquettes*. Since briquettes are firm, uniformly shaped and sized lumps, the danger of spontaneous combustion is completely overcome. Briquetted fuels possess improved storage characteristics and are very easily handled.

Powdered fuel can be handled as a fluid, and since there are very definite advantages in burning a fluid material, large installations are turning to the use of powdered coal. Some of the advantages of burning powdered coal are:

1. Combustion is easy to control. Fuel supply can be quickly started or stopped.
2. Easy adjustment to correct amount of air. Large excess of air, and corresponding loss of heat as sensible heat of the greater amount of flue gas can be avoided.
3. The ash is more easily removed, since there are no grates necessary.
4. A long flame, especially useful in large modern boilers, can be obtained.

Factors discouraging the wider use of powdered fuel include the following:

1. Because of cost of equipment for grinding, the installation is limited to large coal burning units.

2. Considerable cost is involved in the grinding operation.
3. Handling a fine dust may mean a dirty plant, and may create a dangerous concentration of coal dust in the atmosphere.
4. Powdered fuel is impossible to store, so must be used as it is ground.
5. The advent of the newer grates and the use of thin fuel beds have overcome many of the objections to burning a coarser fuel.

Liquid Fuels. *Petroleum* is the liquid fuel of greatest importance. Its various products are tailor-made, so to speak, for specific fuel requirements. Other liquid fuels, such as tar and alcohol, are quite satisfactory for certain purposes, but except in unusual situations, they are too expensive to be used as fuels.

Synthetic liquid fuels have been successfully prepared from gaseous or solid fuels and at least one full-scale plant has been constructed in this country for that purpose. The liquid material which can be thermally distilled from oil shale is another potential source of extremely large quantities of liquid fuel. Fuels from both these sources are still too expensive, however, to compete successfully with liquid fuels made from petroleum, although the cost differential is continually narrowing.

Liquid fuels possess numerous advantages. Some of these are listed below:

1. High heating value—from 18,500 to 20,000 Btu per lb.
2. More uniform than coal or the other solid fuels
3. Easily regulated to secure complete combustion with a minimum of excess air
4. Rate of combustion is changed by means of a valve, and thus may be automatically controlled
5. Fuel oils do not deteriorate if stored in covered tanks.
6. No danger of spontaneous combustion
7. Requires much less labor to handle than does coal
8. Produces no ashes or cinders, little smoke and no dust
9. Easily transferred by a pump through a flexible hose
10. Can be shipped via pipe lines providing easy and cheap transportation, and much more uniform supply.

Liquid fuels would be almost ideal were it not for their cost. Further, there is a limited amount of petroleum available as

compared to coal reserves, and what is available is much more useful for power production than for heat. Liquid fuels are virtually indispensable for the operation of modern internal combustion engines.

Gaseous Fuels. Nearly all the general operating advantages of liquid fuel except the easy storage of large quantities in small space can be obtained by the use of gaseous fuels. Natural gases are available in large supply at very low price at the source, and even manufactured gases can be made at relatively low cost. The manufactured gases are never quite as cheap per unit of thermal value as is the coal from which they are made, but their use nevertheless is widespread because of their convenience.

Natural Gaseous Fuels

Natural gas, largely methane (CH_4), is found in almost every locality where petroleum has been discovered. At one time natural gas was almost valueless. However, with the expansion of gas pipe-lines, it has become relatively expensive even at the source.

Natural gas has a heating value of over 1,000 Btu per cubic foot. Often before it can be dispensed and used it must be stripped of the less volatile hydrocarbons, such as propane and butane, and must often be purified by removal of sulfur, nitrogen, and other compounds which are present. It may also be treated to remove from it any unsaturates such as ethylene (C_2H_4), which are more valuable as chemical raw materials than they are as fuels. Some purification steps may be fairly expensive.

Manufactured Gaseous Fuels

Of all the manufactured gases, *producer gas* is the simplest and cheapest to make, and has the lowest flame temperature and lowest heating value. Producer gas is the combustible gas formed by burning a solid fuel with a restricted supply of air, in such a way that there is a subsequent reduction of carbon dioxide (CO_2) formed in the initial combustion by incandescent carbon in the upper levels of the fuel bed. The resultant gas contains largely nitrogen, carbon monoxide, and hydrogen (from steam which may have been used to cool the grates), and has a heating value of about 90 Btu per cubic foot.

If steam in any quantity is introduced in the producer gas process, considerable quantities of hydrogen and carbon monoxide are formed by the reaction between carbon and water. The resultant gas is known as *semi-water gas*. It has little advantage, except a slightly higher calorific value, over producer gas.

The nitrogen of the air, which is a diluent in both the producer gas and semi-water gas, can be eliminated by using oxygen instead of air as the oxidizing agent. With the production of cheaper liquid oxygen this modification may find extensive use. However, the usual method of nitrogen elimination is through the intermittent water-gas process. In this process the producer is heated by blowing with air for several minutes until the temperature rises to the desired level (blow period). Steam is then fed to make gas until the temperature falls to too low a level to produce rapidly a satisfactory gas (make period). The *water gas* produced by this method is a mixture mostly of carbon monoxide and hydrogen. It has a heating value of 225 to 300 Btu per cubic foot. The presence of the high percentage of carbon monoxide, which is poisonous, in a gas having no odor presents a hazard.

Although the heating value of water gas is appreciably higher than that of producer gas, it still is not high enough to meet municipal requirements. It is therefore passed while hot through a unit known as a carburetor, where it is brought into contact with a petroleum oil sprayed over a heated surface, and then to a superheater where the petroleum gases are further cracked before the gas is passed to the gas-holder. The resultant gas is the so-called *carburetted water gas*. It has a heating value of about 500 Btu per cubic foot, has an odor, and is used extensively as domestic and industrial fuel gas.

Coal gas is made by the distillation of coal and usually in retorts similar to those used for the production of coke. Coal gas burns with a luminous, bright, and often sooty flame. It has a heating value of 500 to 600 Btu per cubic foot.

Oil gas, which is made by the destructive distillation of petroleum, is of little importance. It is likely to contain considerable quantities of unsaturated hydrocarbons and burn with a luminous smoky flame.

Blast furnace gas is another fuel gas of limited use. It is a gas

of low heating value drawn from the vent of a blast furnace. Most of this gas is used to preheat air going to the blast furnace.

Coke oven gas is a by-product of coke production; it is similar to coal gas. Much of the coke oven gas is now used within the steel mills.

Butane and propane stripped from natural gas, and obtained as the lightest ends in the distillation of liquid petroleum, can be liquefied easily, and kept liquid under pressure while they are being transported, sold, and used. Both compounds find wide domestic use on farms and in communities not serviced by natural or regular manufactured gas. They have an exceptionally high heating value.

Considerable amounts of methane and ethane gases are produced as *refinery by-products gases* in the cracking of petroleum. These are often available in limited quantities for general use. They resemble natural gas in properties.

Acetylene gas made by the reaction of calcium carbide and water, or more recently by other methods, is far too expensive to have more than limited use as a fuel. Because of its high calorific value and its ease of transportation dissolved in large volumes in acetone, acetylene is used widely for welding.

7 : THE CONVERSION OF ENERGY

Energy Conversions

- Nuclear energy to heat energy
- Solar energy to heat and chemical energy
- Hydraulic energy to other forms
- Transfer of chemical energy from one component of a system to another
- Chemical energy to mechanical energy
- Chemical energy to heat
- Chemical energy to electrical energy
- Heat to chemical energy
- Heat to mechanical energy
- Heat to electrical energy
- Mechanical energy to chemical energy
- Mechanical energy to heat
- Mechanical energy to electrical energy
- Mechanical energy from one form to another
- Electrical energy to chemical energy
- Electrical energy from one form to another
- Electrical energy to mechanical energy
- Electrical energy to heat

The techniques available for the conversion of energy are numerous and varied because of the many different types of energy sources, and of the numerous requirements of energy-absorbing systems. A check list of factors to use as a guide for selecting techniques of energy conversion has two items of fundamental importance, and several of secondary nature. The fundamental factors are:

1. The type and quality of energy available, and
2. The type and quality of energy desired for use.

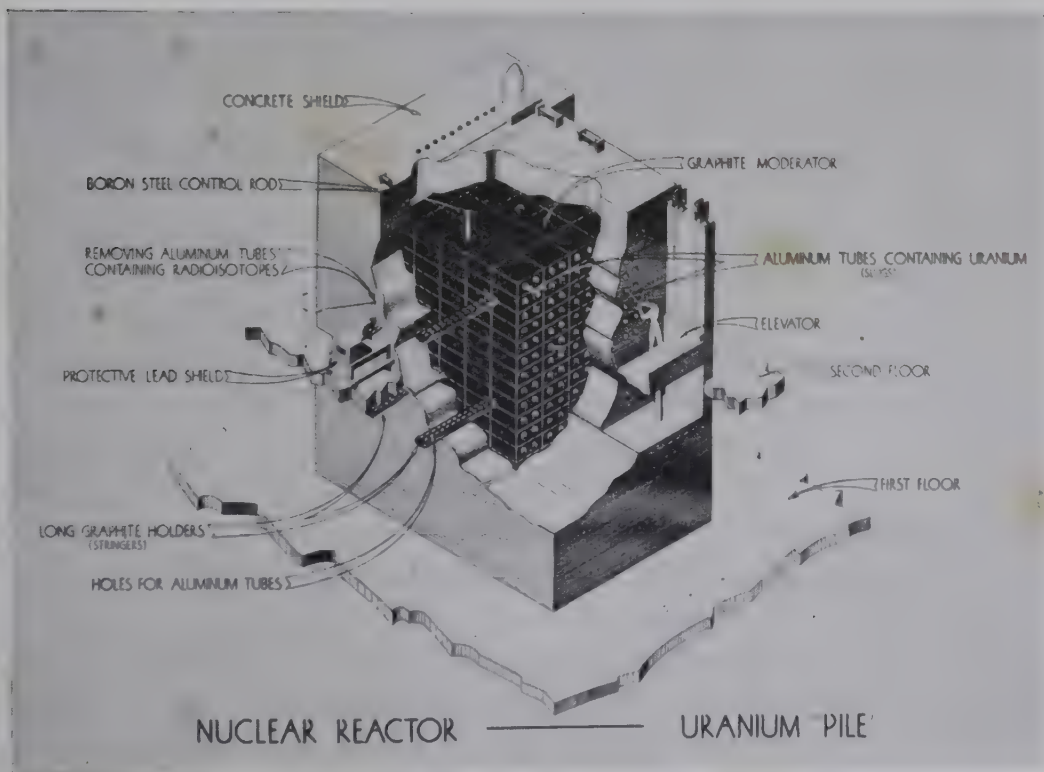
These two alone may fix the choice of techniques, other factors being of no particular consequence. When the first two do allow some latitude of choice, such factors as the following may affect the selection of techniques:

3. Costs (installation, operation, and maintenance)
4. Convenience
5. Cleanliness
6. Freedom from noise or other nuisances.
7. Dependability
8. Safety

ENERGY CONVERSIONS

Conversion of Nuclear Energy to Heat Energy

Because of unusual technical difficulties the commercial application of nuclear energy is perhaps decades away. Its first industrial use—at least the one which is receiving the greatest attention



(U. S. Atomic Energy Commission, Isotopes Div., Oak Ridge, Tenn.)

Figure 44. Nuclear Reactor (Schematic diagram of slow neutron pile).

at the present time—will be its conversion to heat, probably in the form of steam. A controlled release of nuclear energy is effected by the use of nuclear atomic reactors or "piles." The pile consists essentially of uranium enclosed in aluminum tubes which,

in turn, are placed in slots in graphite blocks. The whole assembly is enclosed by a thick concrete shield. The pile activity is controlled by inserting or withdrawing rods of boron steel. In the release of this energy, tremendous amounts of heat are developed at exceedingly high potential levels. This energy must be dissipated very rapidly; it is transferred to fluids (usually water) circulated through tubes extending into the pile.

The major obstacles to the widespread use of nuclear energy are the exceedingly heavy shielding necessary to prevent the exposure of persons in the vicinity of the reactor to nuclear radiation, and the problem of the disposal of the radioactive wastes which are produced.

Conversion of Solar Energy to Heat and to Chemical Energy

Much of the radiant energy falling on the earth's surface is reflected back into space. The remainder is absorbed and stored as heat in the water and land masses of the earth's surface, to be re-radiated when the earth turns away from the sun during the night. The quantity of energy falling on a given area is considerable. For example, more energy than that required to run a 1 hp. motor falls upon a surface one square yard in area when the sun is directly overhead on a bright day. The quantity of energy varies somewhat with the latitude of the area.

Many efforts have been made over the centuries to convert solar energy to heat or mechanical energy successfully. While it can be done, inherent difficulties, such as the low temperature level and the occurrence of nights and of cloudy days, have made impractical every attempt but one—the concentration of salt brines—to use solar energy for direct industrial purposes. Partially successful attempts to use it for heating water and air for domestic use have been made; but here too, the wide variations in intensity, and the fact that the sun's heat is at its lowest average intensity when the heat is most needed, have deterred extensive development.

The conversion of solar energy to chemical energy is of fundamental importance to human existence. It is the energy of the sun, together with carbon dioxide from the atmosphere, and moisture, nitrogen, and other chemical substances which are combined

in the leaves of plants to form plant tissue, that constitutes the basis of existence for all living organisms. The mechanism of this energy conversion has never been completely explained, although many years of research have been devoted to the problem; nor has nature's process for the conversion of solar energy to chemical energy (photosynthesis) been successfully duplicated outside the living plant.

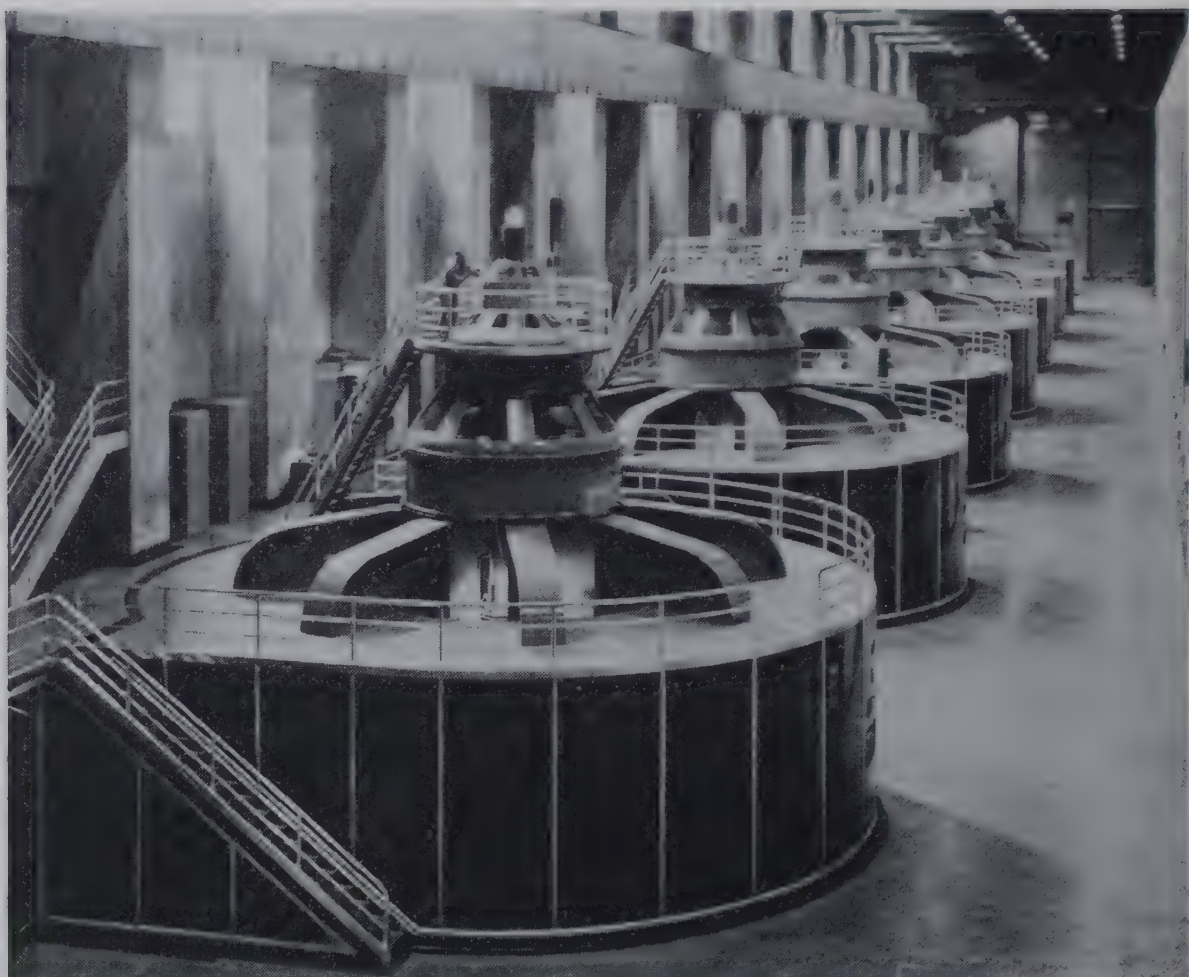
Conversion of Hydraulic Energy to Other Forms

Hydraulic energy exists chiefly in the form of water resting at some level above a discharge point and thus having potential energy of position. When the water is discharged at a lower elevation, its potential energy is converted to kinetic energy by the velocity imparted to it. Hydraulic energy is converted almost exclusively to mechanical energy. This in turn may be used as such, but it generally is converted to other forms for use, notably electrical energy.

There are several types of waterwheels for converting the velocity head of water to mechanical energy. For low pressures (10 to 100 ft. hydrostatic heads) the *axial-flow or propeller type* of water wheel is likely to be used. The propeller may be very large. In appearance, it resembles a large ship's screw. It turns at relatively slow speeds but with tremendous torque. It is fixed in position with a vertical shaft and centered in a vertical draft tube through which the water is conducted.

For intermediate pressures of 50 to 500 ft. head, the *inward-flow reaction turbine* is most suitable. This resembles a huge centrifugal pump set in a vertical position, which is turned by water flowing in from the perimeter of the rotor toward the shaft where it is discharged. In contrast to the propeller-type wheel, which may be located well below the water level in the tail race, the rotor of the reaction wheel is usually located above the lower water level.

Pressures above 500 ft. heads are not often available; when they are, the *Pelton water wheel* is the most suitable unit for converting them into mechanical energy. In this machine the water is introduced through a nozzle or nozzles and is made to impinge upon especially designed cups or vanes fastened to the



(U. S. Bureau of Reclamation)

Figure 45. Power Plant. Nevada wing of Hoover Dam

perimeter of the wheel. The wheel is driven at a high rate of speed by the pressure of the water against the blades. This machine, unlike the other two, does not run with the rotor submerged in the fluid passing through the casing.

Transfer of Chemical Energy from One Component to Another of the Same System

There are a number of examples in chemical engineering practice where energy is transferred from one molecular system to another, without intermediate conversion to heat or other types of energy. Heat may, however, be necessary to establish and maintain proper reaction temperatures; or it may be necessary in some cases to remove heat generated by the reaction so as to adjust the materials to correct temperature levels.

An excellent example of this kind of transfer is found in the

blast furnace for the production of iron. In this unit iron oxide is reduced to free iron by direct reaction with carbon monoxide. The action of hydrogen in reducing a number of substances is similar in character. Many additional examples could be cited. The techniques for bringing about this energy conversion are involved in promoting the reaction itself. They are discussed in a later chapter.

Conversion of Chemical Energy to Mechanical Energy

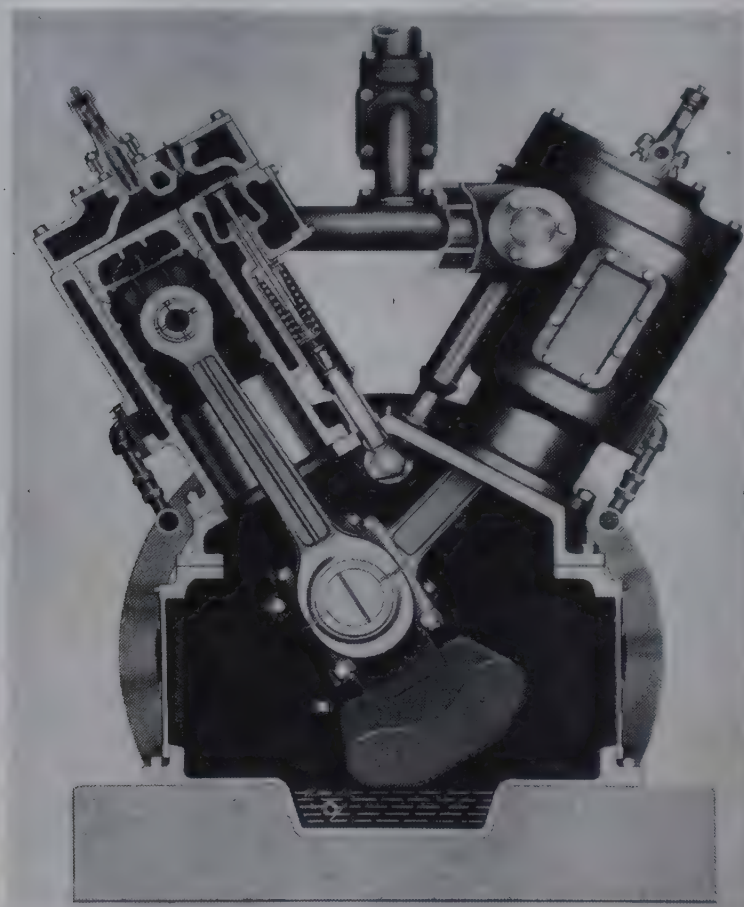
This conversion rarely, if ever, is accomplished directly. The end result may be this conversion, but the actual operation normally takes place in two steps: first, the conversion of chemical energy to heat by an appropriate reaction, followed by a conversion of the heat energy to mechanical energy. Since the intermediate heat energy is in existence for only an instant in the internal combustion engine, the gas turbine, and in any one of the several aircraft jet engines, the use of these devices can be considered as techniques for the conversion of chemical to mechanical energy.

It has long been the goal of engine designers to produce fuel-driven mechanical engines which would be more efficient, operate on lower grades of fuel, and reduce engine weight per unit of power delivered.

The *gasoline engine* has been greatly improved over its original designs with respect to performance and efficiency. Valves, valve design, pistons, the shape of engine heads, better mixing, more positive ignition, and many other factors have contributed their share to the general over-all improvement.

The *gas engine*, which consumes either natural or manufactured gas, is very similar to the gasoline engine except in details of carburetion. This engine is obviously useful where natural gas is plentiful and cheap. Thus it is often used as the prime mover in compressor stations on natural gas pipe-lines. In locations where low-cost gas is available the gas engine would probably be a more efficient, cheaper, and less troublesome installation than either the diesel engine or a steam plant. Its use is indicated in small power installations where the standard steam plant—steam turbine—electric generator arrangement might be too costly.

The *diesel*, another type of internal combustion engine, is taking the place of more conventional steam-powered plants in many new installations. This is particularly true in transportation (ships and railroads), where the lighter weight and greater efficiency of the diesel allows a heavier payload or longer cruising range. Stationary diesel engines often meet similar requirements



(Ingersoll-Rand Co.)

Figure 46. Gas Engine (Sectionalized view)

for industrial use where there is small-to-intermediate power demand.

The *gas turbine*, based on a principle quite similar to that of the steam turbine, operates by the expansion of heated gas through its rotor. It is still in the experimental stages. It promises even greater efficiency and a smoother flow of power than the diesel engine, but operating disadvantages have kept it from being serious competition for the diesel for heavy-duty power production. It is a light, compact, and high-speed unit which has great promise.

The *jet engine*, developed for aircraft propulsion, is currently of little interest to engineers and designers in other fields.

Conversion of Chemical Energy to Heat

It is in this conversion that the bulk of the chemical energy is utilized, and whole branches of the engineering profession have been built up around it. With a billion or more tons of coal being converted to heat energy each year, it can be understood readily why attention should be given to improvement of the techniques by which it is effected.

The conversion of a fuel to heat energy must be controlled and must be conducted in a closed space if the heat produced is to be used for industrial purposes. Further, it is often necessary to transfer the heat to an intermediate material, usually steam, which is used to carry the heat to the consuming system. Consequently, the heat conversion system always consists of two units, and often of three. The burner and fire-box, or enclosed space, are the two indispensable parts; the steam chest or heating section is the third.

Fuel Burners. Fuel burners must be carefully designed to accommodate best the fuel which it is desired to consume. Modern construction takes into account many factors relating to the combustion of fuels. Some of these factors are:

- a. Control of flame size, avoidance of "hot spots"
- b. Control of fuel and air supply
- c. Uniform combustion of all fuel
- d. Ease of operation
- e. Positive removal of ash
- f. Adequate but not excessive draft.

Gas burners are usually relatively simple devices. For small installations a burner resembling the laboratory gas burner is perfectly satisfactory. The gas is passed through a jet, and as it passes through the tube of the burner, open vents around the base permit air to be drawn into the mixing tube by the aspirating action of the jet. The major problem in using this burner is the difficulty of obtaining a velocity of the gas-air mixture greater

than the speed of flame propagation to prevent "strike back" in the mixing tube.

In larger installations both air and gas are brought to the burner under pressure and are led to the mixing chamber through separate nozzles, the amounts of each being carefully controlled. If flame length is too great, partial pre-mixing of gas and air with a larger nozzle from the gas feed of the burner will usually solve the problem.

Oil Burners. In order to fire a liquid fuel successfully it must be atomized and burned as a fine spray. Any of the several atomizing nozzles may be used successfully for this purpose. The mechanical spray nozzle is sometimes to be preferred because of the large quantities of fairly heavy fuel which must be sprayed. Oil burners are provided with adjustable louvers for admitting air. The air may be drawn into the combustion zone by the slight vacuum which is maintained in the combustion chamber. Single nozzles are made to handle capacities up to 600 gallons per hour. If a greater capacity is required, multiple burners are installed.

Coal Firing. Coal may be introduced into the combustion zone either as a fine powder or as granules or lumps. Coal to be fed as a powdered fuel is ground to a fine dust, of which 75 to 80 per cent will pass a 200-mesh screen. The dust may be passed directly to the burners as it is ground, along with much or all of the air which is used to blow the powder from the grinders; or it may be sent to temporary storage from which it is fed to the burners as needed. This fuel, in burning, resembles gas or oil, but differs from oil, in that it is already disintegrated. It is therefore fed by mechanical devices directly into the stream of air in which it is to be burned, and is ignited by the flame in the combustion zone.

One of the difficulties of powdered coal firing is that a flame as long as 50 to 100 feet often is required to consume the coal particles before they are swept from the combustion zone. Powdered coal is somewhat difficult to ignite; it is therefore common practice to install auxiliary gas or oil burners for ignition of the coal. Another disadvantage of a powdered fuel installation is that a large fraction of the ash is blown out of the stack, thus creating dust problems in areas around the plant. The remainder

of the ash, depending on its melting point, is withdrawn as a molten slag or a dry powder.

There was a time when all industrial firing of lump or granular coal was done by hand, the fuel being held on grates in beds sometimes several feet thick. The operation was dirty, it produced smoke, and its efficiency of combustion was diminished by improper burning and poor air regulation.

Industrial firing in all new installations is done by mechanical stokers, even in small heating plants. Smoke abatement ordinances, as well as the general desire of plant management for less wasteful operations, have promoted the conversion of virtually all older plants to stoker firing. Industrial stokers in current use are of three general types: spreader or pusher feed on traveling grates, spreader feed on stationary grates, and underfed types in which fresh coal is pushed into the fire bed from below.

The most popular traveling-grate stoker for medium-size installations is the *chain grate*. This grate is, in reality, an apron conveyor having heavy perforated bars as the conveyor surface. The grate surface moves only a few inches a minute and discharges the ash as the grate passes over the breast roll of the conveyor. The coal bed is maintained at a depth of not over two or three inches. Two types of feeders may be used. The simplest is an ordinary pusher type where a thin layer of coal is spread on the grate surface as it moves out from under the feed and into the furnace proper. The spreader feeder, the second type, is located a foot or more above the grate; from this device the coal is literally kicked out to the grate surface, which in this installation moves toward the feeder rather than away from it.

The feeder of the *stationary grate stoker* is similar in operation to the spreader feeder used with the moving grate. The fuel bed is kept down to the proper level by periodically shaking the ash through the grate into ash pits below.

Underfeed stokers are very similar to the ordinary domestic coal stoker in that the coal is pushed upward into a retort where it is burned. This type is particularly good for the avoidance of smoke, since fresh fuel is never introduced on top of a burning fuel bed. Fuel bed depths as much as three feet are often maintained in this type of operation, and one or several so-called

retorts make up the combustion bed. Ash is broken away from the surface of the coal bed in the retort.

Combustion Space. The shape and size of the furnace in which the fuel is burned are usually dictated by the space required to enclose the flame. Those designed for powdered fuel burning must have much larger combustion zones than those for burning coal on grates.

Walls of the combustion space are made of refractory brick, covered on the outside by layers of insulation, and finally by a common brick or steel casing. To prevent excessive damage to the walls by high temperatures, and to reduce overall radiant temperatures within the furnace, the walls of the furnace are often lined or partially lined with water-filled tubes. These may be plain, or may be finned or studded to give better heat transfer.

The combustion space must be provided with draft to clear it of the gaseous products of combustion and to draw in the fresh air needed for the operation of some types of burners. Natural draft is obtained by erecting a stack, into the bottom of which the hot gases are introduced. Large centrifugal blowers are used for creating a mechanically induced draft.

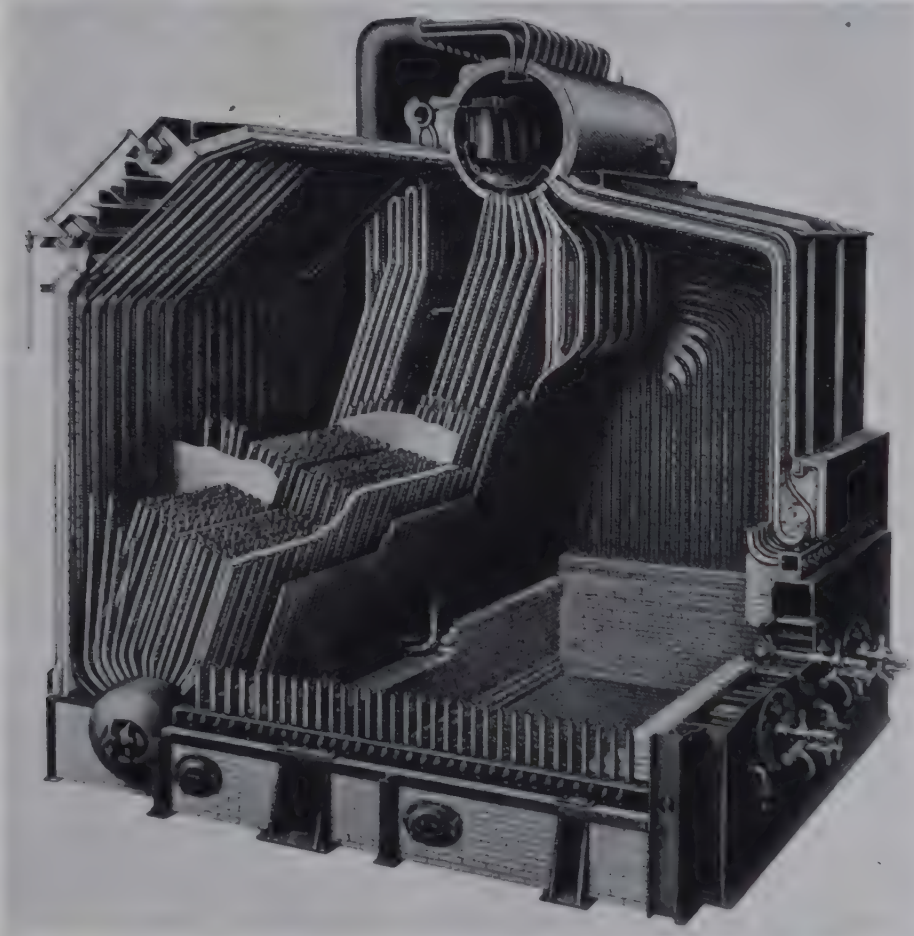
As compared with the stack, the centrifugal blower represents a lower initial investment and provides a more positive control of draft conditions, but costs more to operate and maintain. The much shorter stacks on the fan systems may introduce trouble in the immediate neighborhood by discharging fly ash close to the ground. Nevertheless, all the difficulties encountered in using forced-draft equipment are more than compensated by the more accurate control provided.

Boilers. Most furnaces are operated in conjunction with boilers in which the heat in the burning fuel is transferred to water or other liquid. There are many exceptions to this generalization. Boilers are built according to two general designs—the fire-tube and the water-tube patterns.

Fire-tube boilers are adapted only to small installations and are satisfactory for use only at pressures below 200 psi. In these low capacities, they are inexpensive and, since they require a minimum of furnace wall and little headroom, they are easy to install. The water in the fire-tube boiler surrounds the tubes; the heated

gas goes through the tubes, making one or two passes through the tubes before it is discharged.

In *water-tube boilers*, water is circulated through steel tubes which are supported inside the furnace. In modern industrial practice, the tubes are bent so that the headers can be more firmly anchored. With present day boiler-water treatment, scaling and



(Babcock and Wilcox Co.)

Figure 47. Water Tube Boiler (Sectionalized view).

the necessity for removing scale by tube reaming, which favor a straight-tube design, have been largely eliminated. The design of these boilers is very flexible, hardly any two being exactly alike. The boiler system usually contains such parts as the boiler proper, a superheater, water-cooled walls, and economizers.

Conversion of Chemical Energy to Electrical Energy

Certain chemical reactions can be conducted in such a manner that an electric potential can be created and a current caused to

flow by the energy released in the reaction. The apparatus in which this type of reaction takes place is known as an electric cell. There are two general types of cells: primary cells, in which the chemicals are spent when the reaction is complete, and can be used but once; and secondary or storage cells in which the chemicals can be repeatedly regenerated for further use by passing a direct electric current through a cell which has been partially or completely discharged.

Electric energy is very expensive when generated by primary cells—much less so when obtained from the secondary type. Consequently the primary cell is used only for extremely light loads, where the service is intermittent, or where rough handling or the need for light weight makes the small, rugged primary cell a necessity.

Primary Cells. While a number of primary cell systems have been developed over the years, the only one of commercial importance today is the so-called dry cell which is a modification of the Leclanche cell. This cell employs the system $\text{Zn}/\text{NH}_4\text{Cl} - \text{MnO}_2/\text{C}$.

The dry cell is not really dry at all, but contains the ammonium chloride in a solution which is absorbed in a filler. The zinc goes into solution to form a double salt with the ammonium chloride, and the manganese dioxide acts as a depolarizer (to take up hydrogen). A dry cell, or desiccated cell, is made which has all dry ingredients. The cell is activated when needed by adding water through a small hole in the wax top.

Storage Cells. To be successful in commercial operation, the storage battery, after it has been discharged, must be capable of virtually complete restoration by recharging. Further, it must be rugged and not subject to injury by ordinary handling and usage. Only two cells have been developed so far which meet these requirements. One is the familiar lead cell in which the system is $\text{PbO}_2/\text{H}_2\text{SO}_4/\text{sponge Pb}$. The other is the Edison cell which uses the system, powdered nickel—nickel peroxide/21%KOH/iron dust.

The lead cell is the general utility battery. Extensive research has led to the production of lead storage batteries having high capacity, capable of peak performance under all ordinary operat-

ing conditions, possessing long life and high efficiency, and showing satisfactory resistance to mechanical shock.

Conversion of Heat to Chemical Energy

The technology of the chemical industries includes many examples of the conversion of heat to chemical energy. Any of the so-called "endothermic reactions" fall into this category. The conversion is likely to be very inefficient, however, because of high temperature levels which must often be maintained to provide the driving force for the entry of this energy into a molecule, and because of thermal losses which occur.

Most of the tremendous amounts of heat energy used daily by the chemical industries is used for evaporation, distillation, drying, fusion of materials, and other unit operations, rather than for the introduction of energy into the products of a chemical reaction.

Conversion of Heat to Mechanical Energy

The heat energy of gases or vapors at high temperatures, high pressures, or both, can be converted to mechanical energy with reasonable efficiency. The typical heat source is steam at high temperatures and pressures. This steam possesses high potential energy in a form easy to transform to mechanical energy. This conversion is normally carried out in either the reciprocating steam engine or the steam turbine.

The *reciprocating engine* is characterized, at least in the stationary types, by slow speeds, relatively small power ratings, high efficiency in small sizes, high starting torque, easy control of speed, and generally rugged construction and foolproof operation. *Steam turbines* are high-speed, high-capacity machines, small in physical size for the power delivered, and suitable for the highest pressures and temperatures which can be produced in a modern steam generating plant. Either engine may be used as a utility drive.

Basically, the reciprocating steam engine comprises a steam cylinder, usually double-acting, into which steam is introduced through sliding or poppet valves. The expanding steam, pushing against the piston, creates the driving force.

Steam turbines are of two general types, both operating on the

principle of the expansion of a fluid through carefully designed nozzles, and its conversion at that point to high kinetic energy. If the nozzles are stationary, with the jets of expanding vapor directed against rows of moving vanes, the machine is known as an impulse turbine. If, on the other hand, the nozzles are on the rotating member of the turbine, it is called a reaction turbine. Both types of action may be combined in a single machine, the impulse in a combination unit normally being located at the end receiving the high-pressure steam.

Conversion of Heat to Electrical Energy

There are no examples of the industrial conversion of heat to electrical energy without going through the step of conversion of heat to mechanical energy.

Conversion of Mechanical to Chemical Energy

There are no specific industrial examples of this conversion, with the possible exception of reactions conducted under high pressures, wherein part of the mechanical work done in compression might be considered as being transmitted to the chemical system.

Conversion of Mechanical Energy to Heat

This conversion can be carried out commercially in an apparatus known as a heat pump. The pump does not actually convert mechanical energy to heat but extracts heat from material at a low temperature level and discharges it at a higher temperature level. The heat pump is an application of the compression refrigeration principle. It is designed to have its evaporators absorb heat from wells or other sources and its compressor and coolers so located that the heat is released where it is needed.

Heat pumps cannot raise the temperature very much without serious reduction in efficiency. Consequently their industrial use, at least as far as the chemical industries are concerned, is somewhat limited. The use of this equipment for low-level heating has intriguing possibilities, and a number of installations have been made, most of them still more or less experimental in character. The heat pump is of some interest in plants where heating and

cooling is required simultaneously in different parts of the plant or process.

Conversion of Mechanical Energy to Electrical Energy

This conversion, extremely important to industry, is accomplished in the electric generator, a rotary machine usually turned by direct drive from a steam turbine, some form of the internal combustion engine, or a waterwheel.

Based on the type of electrical energy produced, there are two general types of electric generators. One produces direct current, the other alternating current. The direct current generator, as a primary producer of electric current, has virtually disappeared, and is today used almost exclusively for specific purpose generation, and in this case is often driven by an alternating current electric motor.

Alternating electric current can be transported in far larger quantities and greater distances over a conductor, and with much less loss, than can direct current. Consequently, it is of greater general value. Typical alternating current generators develop voltages, in small sizes, up to about 2,200 volts, and in larger sizes up to 22,000.

It must not be inferred that there are few direct current generators in use. There are literally millions of them installed in the electrical systems of automobiles, in the drive mechanisms of electric or diesel-electric trains and trucks, and in other special equipment where the motors consuming the electric power and the generator for producing it are close together. The heavy starting torques, the ease of speed control, and the possibility of developing high power at any speed have made the direct current motor the preferable one for many services.

Conversion of Mechanical Energy from One Form to Another

In virtually every machine of any degree of complexity it is necessary to convert mechanical energy from one form to another. This involves a change of angular direction, of parallel displacement, of speed, of type of motion, or of any combination of two or more of these. Changes in angle, plane, and speed of rotary motion are accomplished by the use of gears, of which the prin-

cipal types are the spur, bevel, and worm gears; by belts; by chains, including silent link chains and roller chains, and by friction drives using wheels and cones.

The conversion of one reciprocatory motion to another is generally done by using one or more levers, depending upon whether or not the motion is to be reversed. Changes of speed can be made by altering the length of the lever arms. Some changes in reciprocatory motions can be effected by use of complex arrangements of cranks and cams. The change of rotary to reciprocatory motion can be effected by cams of various kinds, crank and connecting rod, and by rack and pinion. All these devices except the cam can be used for the reverse operation.

It is also possible to produce a number of types of motion other than simple rotary or reciprocatory. The planetary motion of a wheel rolling within a tire can be produced from a rotary drive by spur and ring gears, and gyratory or oscillatory motions can be produced by off-center bearings or by cranks.

Conversion of Electrical Energy to Chemical Energy

There are many examples of this conversion, the charging of the storage battery being perhaps the most familiar one. A number of industrial chemicals are made today by electrical decomposition accomplished by the passage of an electric current through a solution of salts. The electro-deposition of metals is of basic industrial importance. The efficiency of most conversions of electrical to chemical energy is excellent. Energy efficiencies of 90 per cent or more are regularly obtained in commercial operations such as electroplating and electrodecomposition reactions.

Conversion of Electrical Energy from One Form or Level to Another

Regardless of the mechanical device used to turn the generator, commercial electric power is normally generated as high-voltage alternating current. Alternating current is the one most often generated and transmitted over the power lines, and since high voltages permit the use of smaller conductors, voltages in excess of 10,000 volts are in regular use. Many industrial plant power-generating systems are cross-connected with commercial power

lines; these must, of necessity, generate power of the same kind and characteristics. For chemical use, however, it may be necessary to use direct current, or to use alternating current of much lower voltage.

To lower the voltage of alternating current, the stepdown transformer is used. In this unit the incoming and the outgoing electrical impulses pass through coils which are insulated from each other but are connected through a magnetic circuit. The relative number of turns in the two coils determines the voltage induced in the secondary or outlet circuit.

The conversion of alternating to direct current is somewhat more complicated and the equipment for doing it much more expensive. The older method of conversion, and one still widely used, is the motor-generator set in which an electric motor drives a direct-current generator. This is the cheapest method for reasonably small output. The rotary or synchronous converter is widely used in larger installations for converting alternating to direct current. In this unit, alternating current is supplied to turn a single rotating element operating as a synchronous motor, and by use of a commutator, direct current is withdrawn from the same rotating element.

When high direct-current voltages (600 volts or more) and high capacities are required, the tendency in modern practice is to replace the rotary converter by one of several types of rectifier. The mercury-arc rectifier is most used. Other rectifiers such as the thermionic tube, copper oxide, and selenium types have been developed for various voltage and current requirements.

Conversion of Electrical to Mechanical Energy

One of the major reasons for the universal use of electrical energy is the relative ease and efficiency with which it may be converted to mechanical energy. The electric motor can be started and stopped merely by pushing a button; its starts and stops are smooth; its speeds can be made variable; it will operate under considerable overload; it needs to vent no fumes; it is virtually noiseless; and it needs no clutches to permit it to build up to operating speed before the load is applied.

Electrical energy may be converted to mechanical energy by

two principal devices: the electromagnet in its several forms, and the electric motor, supplied by either direct current or alternating current.

Electromagnets are widely used in various types of relays, and are used in large sizes as lifting devices. Applications of electromagnets in electromagnetic separators are extensive. The use of the solenoid and magnet as vibrating devices has been mentioned in a previous chapter, as has the use of the solenoid for remote valve control. Electromagnets may be activated by either direct or alternating current. The magnetic field using direct current is steady, while the field of alternating current changes or vibrates with the alternations of the current. The alternating current magnet can, however, be given a special construction which will dampen the vibration.

The *solenoid*, which is a specialized version of the electromagnet, consists of a hollow coil of electric conductor wire, into which a movable iron plunger or rod is vigorously drawn when an electric current is passed through the coil.

Electric Motors. Electric motors are built in a wide range of power ratings and are constructed in many different styles for the various service requirements. The major division of motors is based upon the type of electric current used—whether direct or alternating. There is some overlap here, however, for many fractional horsepower motors are built which will operate satisfactorily with either type.

Direct Current Motors

The motor designed for direct current operation is almost a duplicate of the direct current generator. If the field circuit of the motor is connected in parallel with the armature it is a so-called *shunt motor*; if the field and armature are in series, it is known as a *series-connected motor*; or if there are both shunt and series field coils, the machine has what is known as a *compound winding*.

The shunt motor is used in many stationary applications because of its uniform speed characteristics, while the series motor, because of its high starting torque and variable speed, is favored for applications in transportation.

Alternating Current Motors

There are many styles and types of alternating current motors available. They are usually classified as to phase, there being single phase and polyphase motors. They also may be classified as to operational characteristics; thus there are synchronous, induction, and repulsion type motors. Because of superior power characteristics, the *polyphase motor* is used on all applications above 7 1/2 horsepower, and on a majority of motors down to 1 horsepower rating.

Polyphase synchronous motors are rather difficult to start. As the starting of synchronous motors requires a series of steps, this type is not satisfactory for intermittent service. However, its use on a power circuit improves the power factor of the system, thereby effecting a saving in electric power costs. Consequently, synchronous motors are very often used in locations where the required motor rating is large and where it will normally run continuously, often for days or weeks, without being stopped.

The *polyphase induction motor* (squirrel-cage type) is popular because of its rugged construction, its lack of moving contacts, its ability to carry much heavier-than-rated loads for short periods of time without stalling, and its operation at uniform speeds at any load up to its maximum rating. The starting torque is only fair, but can be improved by special construction. Speed adjustment in this type of motor is difficult.

A *polyphase brush-shifting motor* is built in which speed can be varied at will by changing the relative positions of the commutator brushes.

Single-phase motors, because of rather poor power-loading characteristics, are usually built only in the fractional horsepower sizes. Arrangements such as the split-phase starter, shading-pole starters, and the repulsion starters on induction motors, series motors, repulsion motors, and repulsion-induction motors are all available. Many modifications of virtually all these basic patterns have been made. The types of motors thus available are numerous, but normally any style will perform satisfactorily for the light service required of these motors.

Conversion of Electrical Energy to Heat

The high temperatures which can be produced with the convenience and cleanliness of electric heat makes it of unusual interest to the chemical processor. Its high cost as compared with heat obtained from the combustion of fuel is the one factor which limits its use.

Electrical energy can be converted to heat in four different ways, each having some particular features which make it of special interest. The techniques available for this conversion are resistance heating, the electric arc, induction heating, and dielectric heating.

Resistance Heating. In resistance heating the heat is developed by the passage of an electric current through a resistance wire. It may also be developed in granular masses of material of low electrical conductivity, and in semi-conducting liquids.

Wire or Ribbon Resistors. The resistor wire may be used bare, it may be encased in a metallic sheath, or it may be enclosed as the filament in a lamp. Open resistors are certainly the cheapest of the heating elements, and for many purposes are thoroughly satisfactory. They are frequently operated at a temperature level high enough to transfer appreciable quantities of heat by radiation. The open resistor is used industrially in cases where radiant heat can be utilized without danger of fire, and also where the heater can be immersed in the material which is being heated without shorting out the heating element.

The heating element in which the resistance wire is sheathed in a tube or other protective casing is increasing in popularity. The resistance wire may be imbedded in a loosely packed filling inside the tube, or it may be supported inside the tube in spaghetti-like tubing or on a mica frame. The resistor is thus completely separated from the medium which is to be heated. This heater can be immersed in liquids, imbedded in the walls of a furnace, or subjected to other rough treatment.

The infrared lamp is of interest because its heat is transferred by radiation to the object being heated, and hence will heat it rapidly on the surface. Perhaps the most important feature of the lamp is the enclosure of the actual heating element within

the bulb, thus allowing the unit to be safely used for the evaporation of the volatile and flammable solvents used as thinners in industrial finishes.

Granular Resistors. If carbon or material of similar character is ground and pressed together in a compact mass and an electric current is passed through it, high temperatures will be developed. In the initial stages of any operation this heat probably is developed largely by the thousands of small arcs which are struck in the mass; but as heating continues, and fusion or partial fusion of the mass takes place, the material is heated by internal resistance. These furnaces develop temperatures higher than any other heat-producing industrial unit, probably approaching 4,000° F. in the interior of the furnace.

Molten Resistance Materials. Substances such as molten salt are often used for heat-treating baths. The salt in these baths is melted by means of an electric resistance element, and can be kept molten by placing an electrode in the bath, using the container as a second electrode, and passing on electric current through the bath. Heat for fusing the electrolyte in the aluminum furnace is produced in the same way.

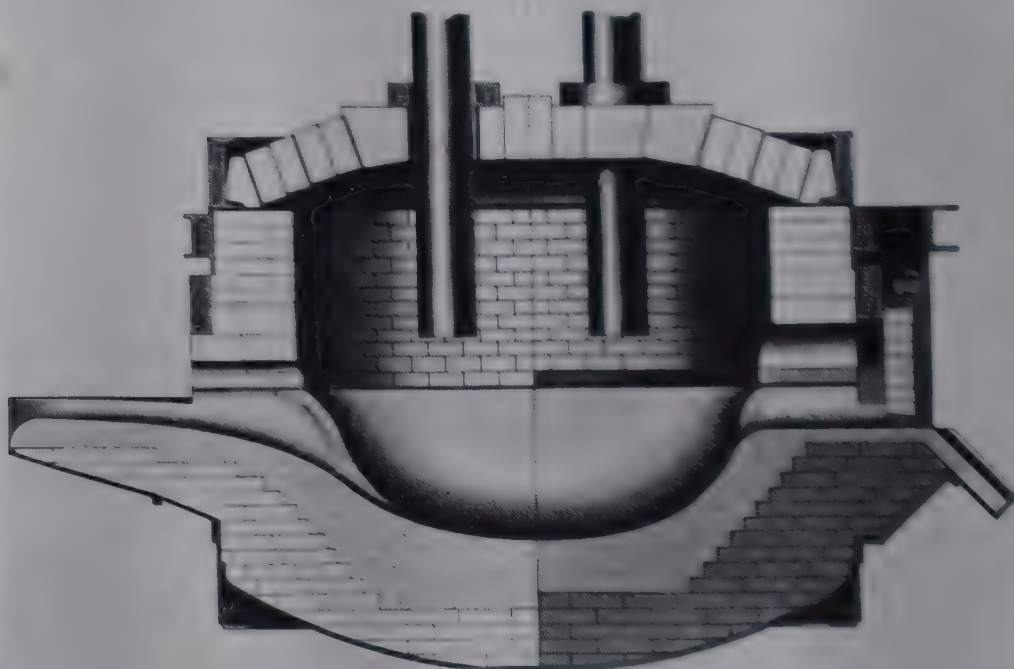
The Electric Arc. This method of converting electrical energy to heat finds wide use in industry as a means of producing high temperatures in such materials as metals and other conductors which might be damaged by exposure to combustion gases. Arc furnaces are of two general types. In one the arc is struck between carbon electrodes directly above the contents of the furnace, and the heat is reflected downward upon them. In the other type the arc is struck between the electrode and the contents.

Induction Heaters. In the induction heater a primary coil like that of a transformer is placed around the substance to be heated. Thus, the material (if iron or steel) or the container becomes the secondary of a transformer. The eddy currents induced within the material or container by the alternating magnetic field flowing against the internal resistance of the materials produce the heat effect.

The electronic, or high-frequency induction furnace utilizes frequencies of 100,000 to 500,000 cycles per second produced by

electron-tube oscillators. Materials placed in this furnace are heated extremely rapidly on their outside surface. Metals can thus be case-hardened without changing the properties of the interior mass of the metal.

Dielectric Heating. Dielectric heating, another achievement based on the electron-tube oscillator, can produce heat evenly



(Herbison-Walker Refractories Co.)

Figure 48. Electric Arc Furnace (Cross section).

through thick sections of non-conducting material, such as plywood or thick molded plastic pieces.

Frequencies of one to thirty million cycles per second are necessary for this technique, and electron-tube oscillators must be used to produce them. The heat is produced by the material functioning as a dielectric between the plates of a condenser, whose plates are charged by the rapidly oscillating electric current. There is little actual flow of electric current, even though the potential drop across the condenser is quite high.

This method of heating is expensive because of the initial high cost of the heating unit, and the very low heat efficiency obtained.

8 : THE STORAGE, DISTRIBUTION, AND CONSERVATION OF ENERGY

Energy Storage

The Distribution of Energy

Methods of energy transmission

Long distance movement

Short distance movement

Chemical energy

Mechanical energy

Electrical energy

Heat

The Conservation of Energy

Improved efficiency in heat propagation

Reduction of heat losses through walls

Improved methods of heat use

Salvaging waste energy

ENERGY STORAGE

It is indeed fortunate that tremendous quantities of energy were stored in prehistoric ages in the form of coal, oil and gas. Perhaps the one thing most woefully lacking in all of our industrial technology is a satisfactory method for storing energy once it has been obtained from the natural stores of solar energy, fuels, or hydraulic energy.

Energy, once released, is completely transient, being dissipated almost immediately in the form of heat. The only exception to this is the storage battery, which is the only energy storage unit now available to which energy can be transferred, held indefinitely, and then released at will in almost quantitative amounts. However, the storage battery is too bulky and its capacity too small per dollar of investment to have applications as a storage unit beyond those purposes for which it is now used.

Therefore, neither the storage battery nor the possibility of

converting mechanical energy back to hydraulic energy has any industrial significance. Certain delaying actions on the expenditure of energy are of some interest. Heat is sometimes temporarily stored in water which is held in insulated vessels, or occasionally accumulated in beds of broken solids. Steam accumulators are installed in conjunction with many boilers to level out momentary fluctuations of energy supply and demand. Energy from any of these storage units is rapidly lost to the atmosphere; the higher the temperature level of stored energy, the more rapid the loss.

There is no way to store electrical energy, as such, for more than an instant. Condensers of various kinds will allow some accumulation of electrical energy, but only in small quantity and for a short period of time at most.

It is possible to store mechanical energy, as may be witnessed in the winding of any clock or watch, or mechanical toy. However, the amounts stored are almost infinitesimal.

THE DISTRIBUTION OF ENERGY

The transfer of energy from one location to another, or from one system to another is the subject of extensive thought and endeavor. The search for improved techniques, and the study of the mechanics of those already in use, occupies the creative effort of many scientists and engineers. In selecting a technique for the transfer or distribution of energy in one of its various forms, consideration should be given to the following factors:

1. Character of the energy to be transferred
2. Distance energy is to be transferred
3. Amount of energy required by consumer
4. Average and maximum rates at which energy must be transferred
5. Efficiency of energy transfer.

METHODS OF ENERGY TRANSMISSION

The movement of energy can be roughly divided into two general classes depending on the distance of movement.

Long-distance Movement

Chemical Energy (Fuels). The energy stored in fuels is the only form which can be moved without restriction. Fuels are solid, liquid, or gas, and hence can be moved to any location, as can any semi-inert substance. The only difference is that fuels, since they are combustible, and in some cases explosive, are somewhat dangerous to handle and store.

It may be uneconomical to transport some fuels for any great distance. It is necessary, however, to transport them to some areas of the earth's surface, regardless of the cost. In these cases it is most economical to transport fuels, such as petroleum, which have a high heating value per unit of weight, and which can be consumed most efficiently in the production of other forms of energy.

Electrical Energy. In this country there are great networks of electric power distribution lines spreading out from central power stations to factories and homes. Most of these power nets and the generating stations are operated by a number of privately owned companies although many are under public ownership.

Power transmission lines will carry electric power at high voltages with far less loss than at lower voltages. Hence, for long-distance lines, the generating voltage of, say 2,300 volts, is stepped up in transformers to a line voltage of well over 100,000 volts, and then reduced to more usable voltages in transformers at the terminus. Limiting factors in transformers, in the lines themselves, and the towers, insulators, and other parts of the transmission system, may prevent voltages from going much higher than present levels. Even with high voltages the power loss may, on long lines, become an appreciable fraction of the energy introduced at the power station.

The longest distance electrical energy can be profitably transported on transmission lines is about 300 miles. Transportation for this distance is justified only because the source is fixed by natural factors as, for example, in the case of large hydroelectric plants. When coal is to be used as an energy source, it is normally cheaper to haul the coal a greater distance and locate the power plant closer to the market.

There has been some conjecture, and actual research, on the distribution of power by methods similar to those by which radio frequency energy is transmitted. While power can be projected a short distance in this manner, it is not practicable because of the enormous losses which occur.

Hydraulic Energy. Hydraulic energy is usually converted to mechanical energy and mechanical to electrical energy, within a few miles, at most, of the location of the power source. While it might be feasible to transport water through longer distances in conduits, the pressure drop due to friction may be great enough to absorb most of the energy initially available.

Mechanical Energy. No methods are available for transmitting mechanical energy for more than a few thousand feet. Mechanical energy is transmitted by rotary rods, for example, in oil-well drilling rigs, by rigid rods or taut cables operating pumps or other machinery some distance from the power source, or by flexible cable on winding drums which operate hoists, or trolleys, sometimes thousands of feet from the drum. All of these are extensions of the same methods used for shorter distance transmission of mechanical energy.

Heat. The only industrial method for transporting heat for any distance is to convert the heat to high-pressure steam and to transport it in this condition. Hydraulic losses in the movement of material in a pipe, and thermal losses to the outside atmosphere, even through well-insulated pipe lines, fix a practical limit of a very few miles at best.

Central heating plants to furnish steam for heating purposes are common today. Virtually all large industrial plants have a single steam plant to furnish power, heat, and process steam for the entire plant and offices. There are even a few installations where by-product (medium- or low-pressure) steam is transferred from a large steam-power electric station to an industrial user.

Short-distance Movement

Chemical Energy. As previously pointed out, chemical energy (fuel) is solid, liquid or gaseous in nature and can be handled in ordinary material transportation devices for short as well as long distances. A common procedure for the movement of

chemical energy is to convert it to heat and conduct it from the point of origin to the absorbing system in that form.

Mechanical Energy. The selection of a method of mechanical power transmission must incorporate conclusions based on the following factors:

1. Relative positions of drive and the equipment to be driven
2. Speed of drive
3. Relative speed of the two machines (driver and driven machine)
4. Power required
5. Type of motion to be transmitted
6. Efficiency of drive
7. Ease of installation and operation.

There are a number of techniques for transmitting mechanical energy from one place to another, or from one machine to another, and a number of devices for effecting this transfer. Mechanical energy applied at one point can be transmitted to another by means of couplings, clutches, rotating or reciprocating shafts, cables or ropes and drums, belts and pulleys, chains and sprockets, gear trains, and variable-speed drives.

Couplings. Couplings are used to connect a rotating shaft of a motor to the shaft of a driven machine, and to join sections of a long rotating or reciprocating shaft. Couplings are constructed in two types, rigid and flexible. In permanent installations where accurate alignment can be secured, the rigid coupling is most appropriate. In cases where perfect alignment cannot be attained easily, use of the flexible coupling is indicated. Couplings in general have one disadvantage—the speed and direction of rotation of the driving and driven shafts must be the same.

For drives where excessive misalignment is encountered, the *universal joint* can be used as a shaft coupling. The universal joint will not allow appreciable parallel misalignment but it will function satisfactorily with angular misalignments of as much as 45° .

The *flexible shaft* has proven to be an extremely useful device where angular misalignment of 90° or more and large parallel offsets are encountered. The flexible shaft usually is made for

reasonably light duty work, but it should not be overlooked as a possibility for a shaft coupling where the shaft of a driven machine must be placed at a considerable angle from the power shaft.

Clutches. Many engines and some electric motors cannot be started at full load. They must be started with no load and brought up to operating speeds before the load is applied. The clutch is a device which allows this to be done. After it becomes engaged it continues to operate somewhat as a flexible coupling.

Clutches are available in two general styles: the mechanical clutch, and the more modern hydraulic clutch. The mechanical clutch is more positive in its action, it is older and therefore more familiar to many people, and much more in demand in industry than the hydraulic clutch. A third style, the magnetic clutch, which shows great promise, is still in the development stage.

The *friction clutch*, the more widely used mechanical clutch, consists of three parts: a disk, cone, or ring faced with a friction material and attached, normally, to the power-receiving shaft; companion metallic disks, hollow cones, or blocks which engage the friction surface, and are fastened to the drive shaft; and a mechanism to press the metallic surface against the friction surface and to maintain this contact. These clutches will operate satisfactorily at speeds up to 2,000 rpm, and will transmit loads, when engaged, with little or no power loss. They operate smoothly and require little attention if properly installed.

Where speeds are low (below 60 rpm) and where shock is of little consequence, a *jaw clutch* composed of two sets of interlocking jaws fastened to the driving and driven shafts is very satisfactory. This clutch is very rugged and is to be recommended in those cases where it will meet the above requirements and where loads are unusually heavy.

The *hydraulic drive* is a device in which a liquid is set in motion by the pump-like action of vanes attached to the end of the driving shaft. This motion is transmitted to similar vanes attached to the driven shaft. This clutch is not quite as positive in action, however, as is the friction clutch.

The principle of the *magnetic clutch* is that certain liquids

filled with powdered magnetic material, and normally quite fluid, will solidify when placed in a magnetic field. This liquid, held between two plates, one driving plate, and one to be driven, will theoretically form an effective drive if the two plates are magnetized.

Shafts. Although little consideration is normally given to the subject of shafting, most of the mechanical energy produced by a motor leaves in a turning shaft, and most of the energy used is conveyed in the same way to the machine using it. Mechanical energy can be transmitted up to thousands of feet from the point of origin to the point of use through the use of rotating steel shafting.

Shafts are often used also to transmit reciprocating motion. Deep-well reciprocating pumps require long reciprocating shafts or rods. In many deep-well pumps the weight of the pump rod is enough to force the piston downward and only the lift stroke need be powered. In horizontal applications it is necessary to drive the shaft in both directions.

Bearings. A necessary adjunct to any kind of a shaft is a support which will allow it to move freely and which will, at the same time, keep it properly aligned and free from wobble. Such supports are called bearings.

Bearings are available in three major types, with numerous modifications of each. The basic types are sleeve bearings, ball or roller bearings, and oilless bearings.

Sleeve bearings are used in industrial applications only at relatively slow speeds, 400 rpm or less.

Ball and roller bearings, the so-called "anti-friction" bearings, are very satisfactory for all speeds; they will take heavy loads; they are built in types to accept heavy endwise (axial) thrust; and are so generally desirable that they are slowly displacing sleeve bearings in spite of their higher initial cost.

Oilless bearings are self-lubricating in that they contain, in the porous bearing material or in a solid insert, sufficient lubricant to eliminate the necessity of outside lubrication. They are particularly useful where the bearing must be placed in inaccessible locations. They are cleaner in operation than other bearings, but their life is likely to be shorter than lubricated types.

Cables or Ropes. Cables, while often used for transmitting mechanical energy, find their greatest application in lifting operations, where the flexible nature of the cable or rope allows it to be wound around a cylindrical drum. Cables also have the ability to transmit reciprocating mechanical energy around obstructions—something difficult to do with a shaft. Since the cable cannot be pushed away from the activating device, it (and whatever it is being used to pull) must be returned to its starting position by gravity, weights or springs. Consequently the cable is not as efficient a drive in some cases as is the rod or shaft.

Belts and Pulleys. Belts and pulleys are a convenient means for transmitting power from one rotating shaft to another. They are more expensive than couplings, require more space for installation, and are somewhat less efficient in power transmission, but possess several distinct advantages. The principal advantage is the ability, through the use of pulleys, to change the speed of a driven machine by changing the ratio of the diameters of the driving and driven pulleys. The ratios are, however, limited to about five to one in either direction. Another advantage lies in the ability to connect motor and machine shafts which are located at different distances above a base and where mounting of the machines to obtain good axial alignment might be difficult and expensive. Several other minor considerations favor the pulley and belt transmission.

Belts and pulleys are made in two styles: the flat pulley and belt, and the so-called "V belt" drive. The *flat pulley and belt* is the time-honored drive. It still finds considerable application as a parallel drive, and has the advantage that it can be used in other than parallel drives. This advantage will probably prevent it from being replaced entirely by the more efficient V-belt drive.

Flat belts are manufactured in four different classes: rubber (or synthetic rubber), leather, canvas, and hair. They are manufactured in various widths and thicknesses, up to 6 feet or more in width and over one-half inch in thickness. All types can be made continuous or can be laced or joined at the cut ends to make a continuous belt. The continuous belts are likely to be best, but require that take-up mechanisms be available on shaft or motor to keep the belt reasonably taut as it stretches.

Pulleys may be made of either cast iron, steel, or wood. All are perfectly satisfactory for almost any service.

The minimum center distances for efficient flat-belt drives vary from perhaps four feet for light loads up to 35 or more feet for heavy loads. Lighter loads and smaller speed ratios permit shorter center distances.

Belt speed should be limited to 5,000 feet per minute. At higher speeds the belt tends to be lifted off the pulleys by centrifugal force and driving efficiency drops off rapidly as slippage increases. Vertical drives should be avoided if possible, since any slack in the belt will cause the belt to hang loosely around the lower pulley.

Belts can be crossed to change drive direction. This may be important in some applications. Crossed belts should be operated only on pulleys of about the same diameter, and are limited to belts 8 inches or less in width. Drives can be arranged so the receiving shaft can be placed at right angles to the drive shaft (twist drive). This is sometimes convenient.

Belt drives can be led around corners by means of loose guide pulleys mounted on intermediate shafts (mule drives). Such drives are not usually satisfactory, however, and are limited to narrow belts.

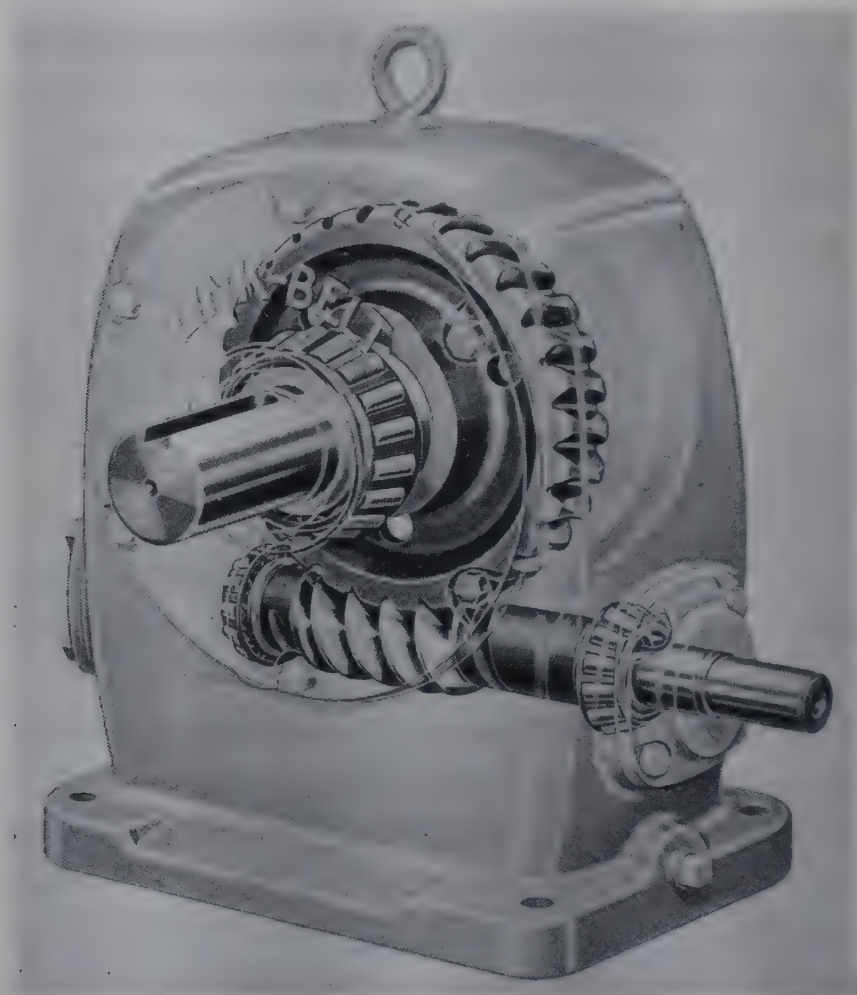
Where it is desired to decrease the distance between centers below that recommended for flat belts, proper belt tension can be obtained by pivoting the motor base so the weight of the motor (gravity type), its rotation (reaction-torque type), or spring loading the base will maintain the tension on the belt.

The *V-belt drive* has been very successful in that it combines excellent operating characteristics with a reasonable cost. The V-belt drive will operate up to speed ratios of 7 to 1; it will permit much closer center-to-center operation of driver and driven sheaves than flat belts; it has a greater load capacity per inch of face width of the pulley; in normal operation there is no danger of the belts leaving the pulleys; and it is unusually rugged and trouble-free.

Most V-belts are manufactured as endless fabric-rubber belts, being sold in a wide range of lengths to suit almost any requirements. The V-belt drive cannot be installed or removed with the ease of the flat belt. Motor or machine bases or anchor bolts

must often be released to give clearance for the belt to be installed. It will give satisfactory service for some misalignment, but cannot easily make quarter turns or be passed around corners like the flat belt.

Chains and Sprockets. The transmission of mechanical energy by means of chain drives is of wide application. Many advantages

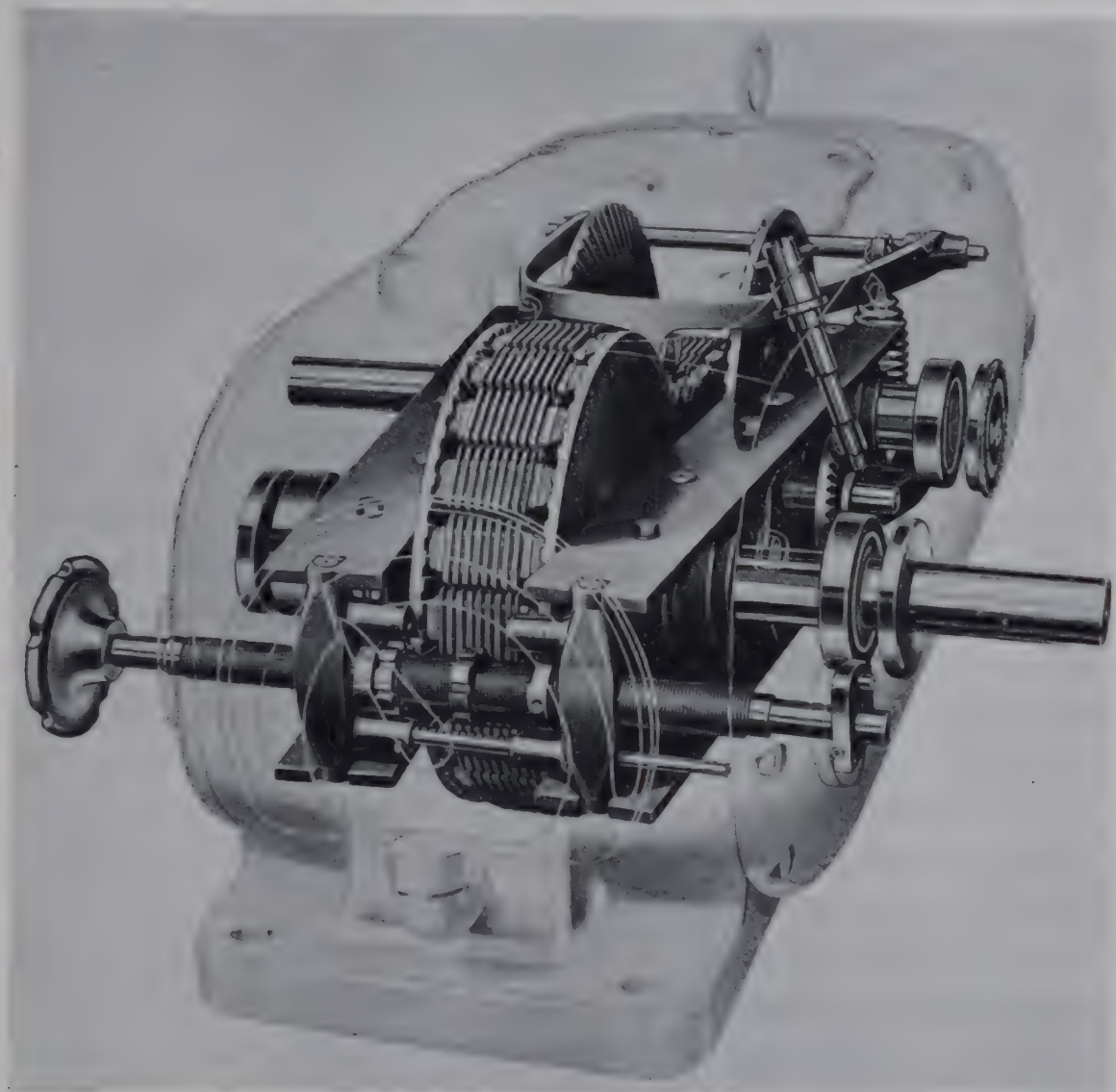


(Link-Belt Co.)

Figure 49. Single Reduction Worm Gear Drive.

are claimed for them. They are highly efficient, they develop no slip so that a positive speed ratio is held, they easily transmit large amounts of power, they can be used on short centers, and they are unaffected by heat or cold. The principal disadvantage of the chain drive is its noise. Since it has moving metal parts in contact, it must be kept well lubricated. Chain drives must be operated at slower speeds than belts. There are three types of chain drives: the detachable link, the steel roller, and the silent chain.

Gear Trains. When speed reduction greater than 6 or 7 to 1 is required, belt drives are not generally suitable. Gear trains usually offer a solution to the problem. The selection of a gear train is governed by the relative speeds required and the relative directions of operation of the two shafts. Costs will be largely deter-



(Link-Belt Co.)

Figure 50. P.I.V. Variable Speed Drive (Phantom view).

mined by such factors as power to be transmitted, smoothness of operation (precision of gear teeth and type of shaft mounting), gear boxes, and lubrication.

Variable-speed Drives. Many modern designs of machinery require minute and accurate variations of speed. Further, speed control must often be rapidly and easily applied. Although it is preferable on large installations to obtain variable-speed opera-

tion by the use of the variable-speed direct-current motor, this is often impractical, and mechanical speed changers must be substituted. There are several of these available.

There are two types of mechanically-operated speed control: the Reeves, which will operate at speed ratios up to 16 to 1, and the Link-Belt P.I.V. which will control speed in any desired ratio up to 6 to 1. The Reeves speed-control unit consists of two smooth-surfaced cone disks with their apexes facing inward. A rubber and wood-block belt operates between them. To vary the speed, the two cones are moved in or out, thus changing the effective diameter of the pulley. The Link-Belt P.I.V. unit utilizes two pairs of toothed cone disks and a laminated toothed chain operating between them.

Electrical Energy. Electrical energy is transmitted by imposing an electromotive force (E.M.F.) upon conductors, insulated from one another, of sufficient size to handle the power transmission required with minimum heating and electrical loss. In this respect it is no different than longer distance transmission. For local distribution of electric power within a plant, however, voltages are likely to be much lower than those used in the transmission lines. Therefore, the conductors are normally larger, occasionally aggregating 10 or more square inches in cross-sectional area. The bus bars for this and similar applications are usually laminated rather than solid to provide better cooling and superior power transmission characteristics.

Heat. The chemical engineer has a fundamental interest in the transmission of energy in the form of heat. Nearly all chemical processing involves the addition or removal of heat, and many textbooks written for chemical engineers deal with the mechanisms for its transmission.

Heat may be transmitted from one region to another and from one system to another by any one or various combinations of three natural phenomena. It may also be held in heated material and the material mechanically transported.

The three natural phenomena for heat transfer are: (1) convection, in which the heat is transferred from a point of entry to a mass by material currents set up within the mass; (2) conduction, exemplified by the movement of heat from one end of a

metal rod to the other; and (3) radiation, that phenomenon by which heat can be transmitted like light, without affecting the space between the radiating and receiving surfaces.

The factors which should be considered in the selection of a technique for the transfer of heat include the following:

1. Permissible maximum temperatures at the point of use
2. Required minimum temperatures in reaction mass
3. Kind and condition of vessel holding the reaction mass
4. Effect of products of combustion on the reaction mass
5. Temperature and operational control necessary
6. Cost of heat, and value of product
7. Properties of the reaction mass, such as volatility, corrosiveness, flammability, chemical stability, sealing properties.

Techniques for Heat Transfer

Heat may be transferred from one system to another by any one of the following methods: (1) It may be produced by the combustion of fuel or the discharge of electric energy and transferred by direct contact with the mass being heated. (2) It may be generated close to the mass, and transferred largely by radiation. (3) It may be generated in or on the walls of the vessel containing the reaction mass and transferred through the wall of the vessel or through the film separating the wall from the body of the material, or both. (4) It may be generated in a body completely separated from that containing the reaction mass, transferred to the reaction body in a gas, vapor, or liquid, and released to the reaction mass through the walls of the container, or directly into the mass itself, or both.

All the several techniques for transferring heat energy from a generating source to an absorbing reaction mass are important, and each has advantages and disadvantages. Further, each technique requires several items of equipment more or less peculiar to its application.

The development of heat within the reaction mass. For the highest temperatures commercially available, the generation of heat within the reaction mass is indicated. The highest temperatures are obtained by electrical discharge; somewhat lower tem-

peratures by the combustion of a fuel. These high temperatures are obtained because there is less loss of heat to the atmosphere, and heat levels do not have to be developed for driving the heat through retaining walls.

The major difficulty with the development of heat within the reaction mass is that if a fuel is used the products of combustion mix with the reaction mass. Electric heat, which does not have this disadvantage, is quite expensive.

Heating by electrical methods. Heat may be produced electrically through the internal resistance of the mass and by arcing between the particles constituting the mass. The furnace walls for this operation are generally formed of a bed of the unreacted materials several feet thick. This mode of operation, producing no combustion products to contaminate the reaction mass, develops the highest temperatures in commercial use. The major disadvantage is the high cost.

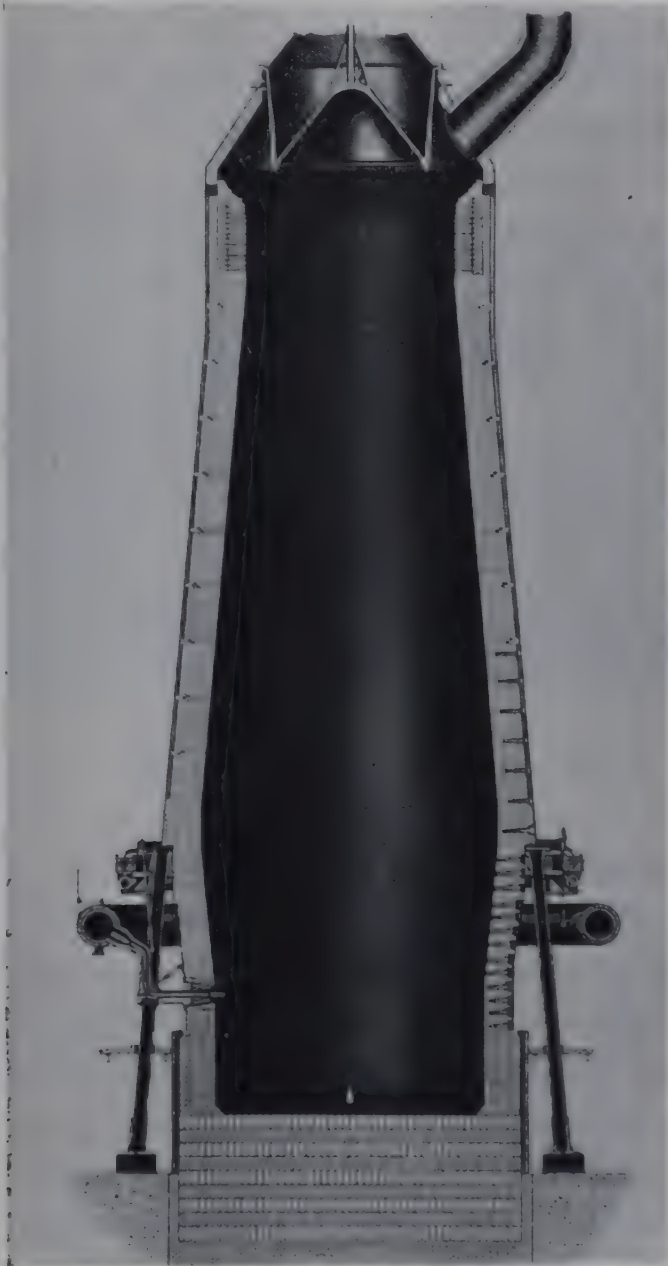
Internal heating of nonconductors by dielectric heating and of conducting materials by high-frequency induction are becoming increasingly important.

Heating by the combustion of fuels. (1) Combustion in a solid reaction mass. The burning of a fuel within a reaction mass is entirely feasible, and is practiced in several large-scale operations. In these operations, both gaseous and solid products of combustion mix with the reaction mass. This is of no consequence in blast furnace operation since the ash is withdrawn as a slag, but in the lime kiln the purity of the lime produced from limerock is reduced. Gaseous fuel can also be burned in contact with a solid mass if the mass retains sufficient porosity to permit the combustion to take place.

The principal problem in these operations, aside from the mixing of combustion products with the reaction mass, is the difficulty of temperature control. Hot spots are likely to develop, channeling is very likely to occur, and overall operational control is poor. Fortunately, in most of the applications of this mode of heating, such lack of control does not give rise to serious loss of yield or quality.

A new development for handling finely divided solids, and generating heat in the midst of a reaction mass is the so-called

“fluidized solids” technique. In this operation the solid, in the form of uniform but very small particles, is suspended in a stream of air; gas is admitted from ports through the side of the furnace and is burned in the floating mass of solid particles. The particles,



(Harbison-Walker Refractories Co.)

Figure 51. Blast Furnace (Section).

after being heated, are discharged from the furnace and can be separated from the gas by appropriate methods.

(2) Combustion in a liquid reaction mass. A combustion unit known as a *submerged combustion burner* is now available which will burn gas, liquid fuel, or even powdered coal under the surface

of a liquid. Both air and fuel are conducted to the burner under pressure, mixed in a mixing chamber and forced into the combustion chamber where they are burned. The evolution of heat and gas in the form of a flame sets up violent agitation within the liquid and thus more or less prevents the formation of hot spots.

The development of heat in contact with the reaction mass but not within it. In cases where the reaction mass is a finely divided solid, where ash cannot be mixed with the material, or where the mass is a heavy viscous liquid like molten steel or molten glass, methods in which heat is released within the reaction mass cannot be used easily. For this service, various types of furnaces have been developed in which energy produced by flames from the combustion of fuels or an electric arc is transmitted by radiation or contact to the mass being heated.

In the *reverberatory furnace* the flames are reflected downward upon the reacting materials by an arch located a short distance above the surface of the material in the reaction vessel. The use of this furnace is limited to those materials which are molten and in which heat transfer is relatively rapid. Temperatures here are high; they are limited only by the softening temperature of the lining of the reverberatory arch. The heat transfer rate is excellent and heat losses are relatively small.

For handling those materials which are virtually solid but may become somewhat plastic when heated, such as the clinker in the manufacture of Portland cement, the *rotary kiln* provides a method of transferring heat by radiation. However, because the kiln rotates, and because the materials being heated come in contact with the furnace walls, the lining must be made of a material more stable mechanically and more inert chemically than that used for the construction of the reverberatory arch.

Still another furnace operating on much the same general principle is the *single- or multiple-hearth furnace* in which the flames or hot gases pass across the surface of the solid material held on the hearths.

The *electric arc furnace* generates heat between the surface of the mass and electrodes suspended above it, or between the electrodes. In either case the heat is radiated downward into the

mass. This furnace develops high temperatures and produces little or no contamination of the material being heated, but is expensive to use.

Radiant electric lamps and radiant electric heaters operate on the same principle as the reverberatory furnace, but at lower temperature levels.

Heat generated in or on walls of container. This method of heating is not too often used as a method for heating a reaction



(Kennedy-Van Saun Mfg. & Eng. Corp.)

Figure 52. Rotary Kiln.

mass because of poor temperature control, the development of hot spots, and rapid deterioration of the furnace walls.

Heating by electric energy. The generation of heat within the iron or steel walls of a container by induction heating has intriguing possibilities, but high costs discourage adoption of this method of heating. Resistance heaters wound around the outside of the vessel or imbedded in or attached to the inside surfaces of the walls of the unit are used in many types of installation. *Electric resistance furnaces* fall into this classification.

Heating by combustion of fuel. In spite of poor temperature control, one of the major disadvantages of direct heating, it does provide higher temperatures than can be obtained by the more common method of heating with steam. There are a number of uses for this type of heating. Water, for example, can be heated by open flames without danger, and is, of course; always heated by open flames in the tubes of a steam-generating plant. While

this is not exactly a transfer of heat to a reaction mass, the mechanism is the same.

Petroleum crudes are nearly always heated in so-called pipe stills or heaters, which are somewhat similar in general construction to a steam boiler. The major difference is that the oil in the heater usually enters a single tube and passes through the heating tubes in series rather than in parallel, as does the water in the steam boiler. The tubular heater of the petroleum industry is of particular interest for two reasons: (1) the temperatures required are ordinarily considerably higher than can be obtained by almost any liquid or vapor which could be heated in an outside heater and transferred to the space within a heat exchanger; (2) and the liquid, being flammable, will not permit direct heating by one of the methods already described.

Heat generated in an outside heater and transferred to the absorbing unit in a stream of material. This method of heat utilization is used widely in the chemical industries. The several disadvantages, such as low maximum temperatures, material loss in the system, heat lost in transit, and the additional expense of the generating heater, are normally not enough to overbalance the important advantage of better temperature control afforded by this method of heating. It is nearly always used if temperature requirements will permit.

Heat transfer media. Water vapor is the most widely used heat-transfer medium. It is cheap, is easily available and readily replaceable in the event of leakage or accidental loss, is non-flammable, nontoxic, clean, and easily handled. It transfers large quantities of heat energy per pound of material as its heat of vaporization. The only objection to the use of water or its vapor as a heat-transfer medium is that at the high temperatures sometimes required, water vapor would have to be maintained at excessive pressures to obtain condensation.

The usual modern procedure in the use of water vapor as a heat-transfer medium is to produce the vapor at elevated temperatures, use this vapor for the generation of mechanical energy in steam turbines, and use the exhaust of low-pressure steam from the turbines as a source of heat energy for chemical processing. This exhaust, or so-called "process steam," is very inex-

pensive as a heat source and is used wherever possible when the temperatures required can be obtained by the condensation of this steam.

Other liquids such as oil, mercury, "Dowtherm" (diphenyls), molten lead, or other molten solids can be substituted for water. All these are more expensive than water; several are either flammable, corrosive, or toxic, or they cannot be allowed to cool after once being introduced into a system. However, temperatures as high as $1,000^{\circ}\text{F.}$ can be obtained with some of these with reasonable ease and safety.

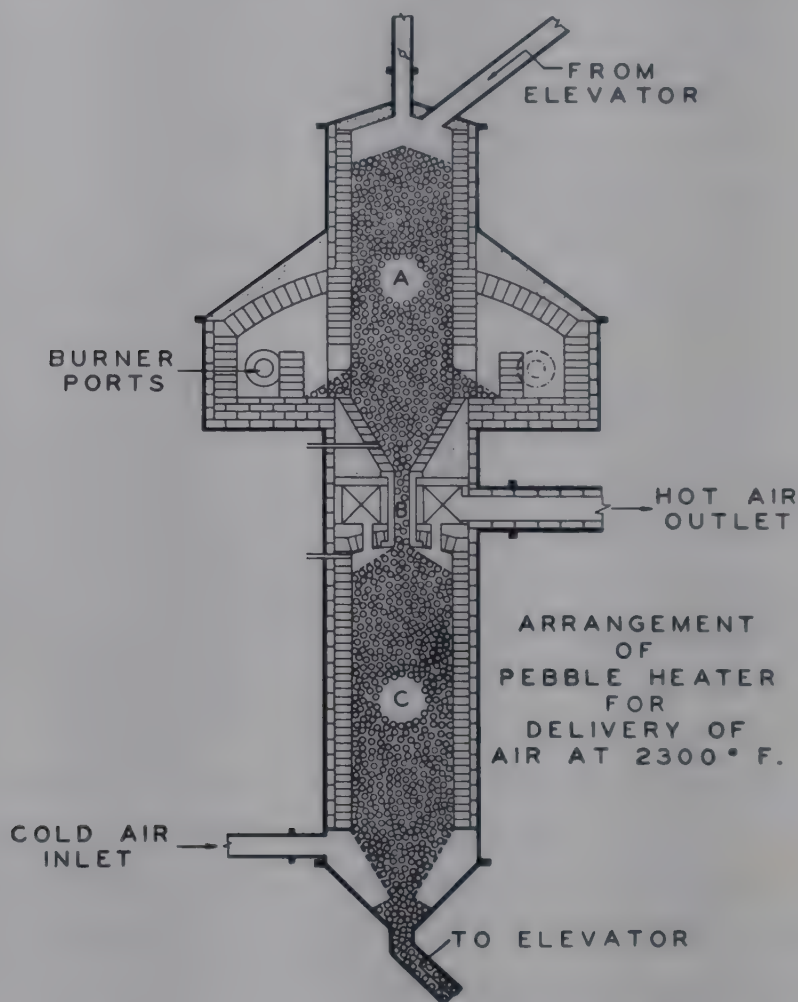
Gas, either flue gas direct from the burner, or air or inert gas heated from some external source, is also used as a heat-transfer medium.

Introduction of heat to the media. Heat is transferred to the liquid heat-transfer media in standard or special designs of the ordinary *steam boiler plant*. If necessary to transfer heat to gas, the transfer is accomplished in either recuperative or regenerative heat exchangers. In the *recuperative exchanger* the gas medium is heated by being conducted through or around thin-walled tubes, the other side of which is heated by the products of combustion of a fuel.

In the *regenerative heater*, the gas medium is heated by being passed over brickwork or broken stone which has been previously heated by passing hot combustion gas through the mass. The cycle is repeated when the temperature of the solid falls too low to be of use in heating fresh gas. These stoves, or heat exchangers, are usually used in pairs operated in such a way that one stove is being heated while the companion stove is being used as a heater.

A continuous regenerative heater known as a *pebble heater* has recently become available. In this heater carefully graded stone pebbles are heated in a chamber. The hot pebbles are slowly discharged through a port in the bottom of the chamber to a second chamber directly below the first. In this section the heat in the pebbles is transferred to a gas flowing through it. The cool pebbles are continuously discharged from the lower chamber into an elevator by which they are returned to the upper or heating chamber.

Circulation of heat-transfer media. In those cases where steam is condensed in the unit to be heated, difference in pressure between the inlet and outlet is more than adequate to assure rapid movement of fresh steam to the heat absorbing surface. Condensate traps are arranged to discharge condensate to the atmos-



(Babcock and Wilcox Co.)

Figure 53. Pebble Heater (A) Pebble heating section (B) Heated pebble delivery pipe (C) Air heating section.

phere, or condensate pumps are used to return condensed steam to the boiler so as to prevent flooding of the heat receiver with liquid.

Heated liquids and gases which do not materially change volume on giving up their heat must normally be circulated by mechanical pumps, or blowers, as the case may be. The moving devices, for obvious reasons, are usually placed on the cooler side of the circulating cycle.

Transfer of heat to the using system. Heat may be transferred

from one of the several media to the reaction mass by either "direct heating" or "indirect heating." In direct heating the steam, vapor, liquid or gas is brought into direct contact with the reaction mass. The heat transfer is at a maximum both in efficiency and speed in this type of transfer. Further, the introduction of the medium as a vapor or gas may assist in the agitation of the reaction mass.

However, mixing the heat-transfer medium with the reaction mass may cause some difficulty. Steam will usually condense in the mass and dilute the reaction mass with water. In addition, the condensed steam cannot be reclaimed. It is obvious, of course, that liquids such as "Dowtherm" or mercury cannot be used in direct heating of a reaction mass.

Gases, which are used frequently as heat-transfer media, may also cause difficulties in direct heating. Their use is certainly limited to liquid or solid heat-absorbing systems. If the gas contains impurities, they may be left behind in the heated mass, or the gas or its impurities may react with the material being heated. Even where these conditions are not encountered, gas used as a direct medium will often carry away volatile liquids or solids as it is vented from the reaction mass; unless this is done as a part of the process, as it sometimes is, the loss of materials may be astonishing.

All this means that the indirect method of transferring heat to the reaction mass is generally to be preferred in spite of lower efficiencies and higher equipment costs.

Indirect heat is conveyed to the receiving system through a wall which separates the heating medium from the heat absorbing system. Exceptions to this general arrangement of heat transfer systems are encountered in special adaptations of the regenerative or pebble heaters.

In the transfer of heat from a liquid or gaseous heating medium to an absorbing system, the heat must pass through a layer or film on either side of the separating wall as well as through the wall itself. In order to obtain rapid heat transfer without inordinately large temperature differences between the two sides of the wall, either large surfaces must be exposed to heat transfer, or mechanical or other means must be used to reduce the thick-

ness of the films, thereby increasing the flow of heat through them. Film thicknesses are reduced by rapid flow of fluid past heat-transfer surfaces. This flow may be stimulated by forced circulation through heat exchangers, or by adequate mechanical agitation within the reaction vessel. Further, the separating wall used should be as thin as possible and made of a material of good heat-transfer characteristics.

Metal should be used for walls where possible, and where it is not, other materials having the best possible heat-transfer coefficients should be selected. Heat-transfer surfaces are often incorporated into the design of reaction vessels as steam jackets, heating coils, or steam chests.

A reaction kettle may be so constructed that its outside walls become the heat transfer surface. The heating medium is held against the vessel surfaces by hollow shells or *steam jackets* surrounding various portions of the reaction vessel. These may be made in a number of patterns to produce better heat distribution, prevent hot spots, withstand high pressures, develop better circulation and higher transfer rates on the heating side. All are, however, of the same basic design.

Heat transfer surfaces are also frequently constructed in the form of *coils* fitting the inside of the reaction vessel and submerged in the liquid to be heated. Steam or other heating media are passed through the interior of the coils.

A third type of heater which can be used for transferring heat to a liquid held in a vessel is the type often used in evaporators. These tubular *steam chests* are either horizontal with steam inside the tubes and the liquor outside; or vertical, with the steam surrounding the tubes and the liquor to be heated inside the tubes.

Heat transfer surfaces may also be completely independent of reaction vessels, being incorporated into units known variously as radiators or heat exchangers.

The *radiator* is a type of heater which is used widely for introducing heat to a gaseous system and resembles the automobile radiator in construction, operation, and appearance. The heating medium is carried inside deeply finned tubes or in other styles of tubes designed to give great surface area per unit of volume

within the tube proper. The gas being heated is circulated over the tubes either by natural or forced convection. The ordinary steam-heated space heater is a common example of this type of heat transfer unit.

Heat Exchangers. Under certain conditions it is not practicable to heat a liquid or gas while it is held in mass in reaction vessels. In such cases, the problem of heating can be solved usually by circulating the reacting liquid or gas through an outside heat exchanger completely separated from the reaction vessel. These heaters are important items in chemical engineering technology.

This arrangement greatly improves the rate of heat transfer, since the circulation of fluids in heat exchangers is usually much superior to that obtained in the reaction vessel. Heating surface in an outside heat exchanger is normally cheaper than an equal amount of surface in a reaction vessel, and it can ordinarily be easily examined, cleaned, repaired, or replaced.

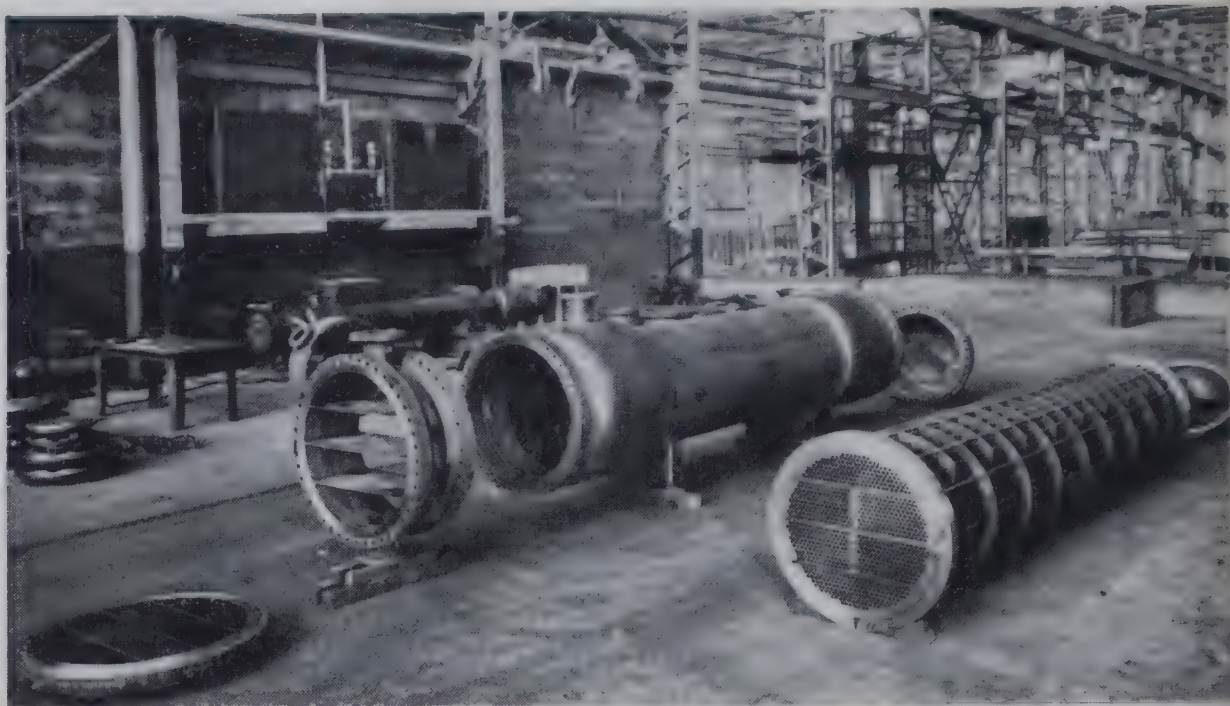
Most heat exchangers are similar in design and operation. The basic pattern is a shell-and-tube design positioned either vertically or horizontally. The usual practice in the distribution of heating medium and heated material is to place that material inside the tube which is most likely to form a scale of deposited solid, since the inside of the tube is much easier to clean.

The standard pattern of *shell-and-tube heat exchanger* may be considered to be the fixed tube-sheet type. This is the cheapest to construct, and the easiest to clean and inspect. However, it is not satisfactory for large temperature differences, and the tube bundle cannot be pulled for inspection of the outside surfaces.

A number of variations in the basic heat-exchanger design can be obtained by changing a few of the parts. For example, a floating head allows for expansion of the tube bundle and gives superior general performance at a somewhat greater expense.

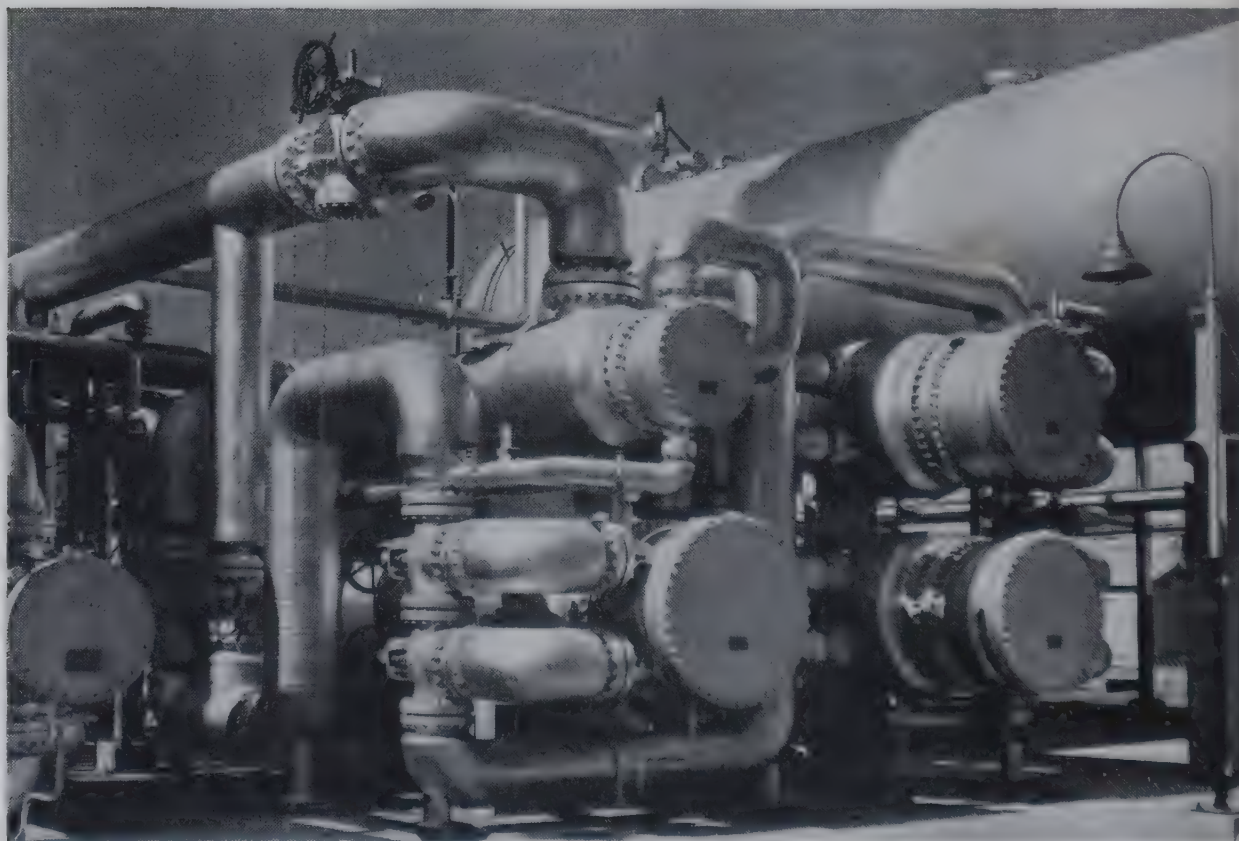
Heat exchangers are built with arrangements for both single and multiple pass to speed the flow of the fluid through the tubes. Baffles in the tube bundle are used to achieve improved circulation and contact of the fluid on the outside of the tubes.

There are several specialized types of shell-and-tube exchangers which vary materially from the standard designs. Heat exchangers



(C. F. Braun and Co.)

Figure 54. Shell-and-Tube Heat Exchanger (Disassembled to show parts).



(C. F. Braun and Co.)

Figure 55. Heat Exchanger Installation.

having coils or return bends instead of tubes, special surface-extending fin arrangements, and other innovations are all available as special designs. For the most part, however, special designs cost so much more per unit of surface area that a larger, less efficient unit can be purchased to give the same operating capacities at less cost than the smaller high-efficiency units.

The *concentric-tube exchanger* is an industrial counterpart of the laboratory glass condenser. These units, designed for counter current flow, give good heat transfer capacity per unit of transfer area. However, surface is more expensive in these heaters than it is in multitube types, space requirements are excessive, and heat losses by radiation from the outside of the jacket tube may be large.

In addition to the several types of shell-and-tube exchanger and the concentric-tube style, several exchangers are available in which unique patterns of construction have been incorporated. These have found only limited use.

THE CONSERVATION OF ENERGY

The conservation of energy, which to the chemical engineer usually means conservation of heat, is another highly important industrial requirement. There are a number of avenues of approach to the conservation of energy. It can be conserved by improved efficiency in the conversion of fuel to heat, by reducing heat losses, by better methods of using heat, and by salvaging waste heat for reuse at lower temperature levels.

Improved Efficiency in Heat Propagation

Since most fuels are consumed to produce heat in the form of steam, it is necessary that considerable attention be directed to steam generating practice if major heat economies are to be realized.

Heat may be lost in boiler operation by incomplete combustion of the fuel; by using too much excess air; by discharging flue gases to the stack at too high a temperature; by uneven steam demand, necessitating frequent release of excess boiler pressure and poor fuel feed control; by the necessity of frequent boiler blow-down to reduce solids content in the boiler water; by

heat losses through the walls of the boiler furnace; and by mechanical losses due to tube failure or accidental shut-down. All these features of operation become subjects for intensive study in any program relating to the improvement of boiler performance.

The Complete Combustion of Fuel. While the ultimate goal of complete conversion of the heating value of a fuel to usable heat by combustion methods has not been reached, the limits in which there is still room for improvement are so narrow that most research is incapable of producing results in keeping with its cost. Much of the lack of efficiency is due to older installations still in use and to the incorrect use of newer equipment. Present smoke abatement regulations have placed a premium on proper combustion practices, and improved efficiency is often the net result of compliance with these regulations.

Most of the development in this field is now concerned with such details as the control of flame length; the establishment of the best heat-transfer conditions; the control of temperature to promote, or prevent, as the case may be, melting or fusing of the ash; the prevention of mechanical failures such as the clogging of fuel lines; the working of grates; and the lubrication of furnace moving parts.

Excess Air. In order to promote complete combustion of a fuel, more air than would be theoretically required is always introduced. This excess air establishes conditions which drive the combustion reaction to virtual completion in the few seconds that the reaction can continue in the combustion zone. However, excess air causes a direct heat loss in its sensible heat as it is swept out the flue with the exhaust gases.

New burner designs make it possible to reduce excess air and still obtain excellent combustion. Coal, once burned in deep beds and often needing well over 100 per cent excess air to secure reasonable combustion, can now be burned in 50 per cent or less excess air with superior results. Oil burning has likewise been improved. It has always been possible to consume gas in air quantities only slightly over theoretical, which is one of the reasons why gas can be burned so much more efficiently than other types of fuel.

Innovations such as secondary air ports, recirculating devices, and mixing baffles have been introduced to improve the operation of furnaces.

Sensible Heat in Flue Gases. Since over twelve pounds of gas is produced in the combustion of one pound of carbon with air, if the gas leaves the furnace at temperatures several hundred degrees above atmospheric, heat losses may amount to more than 10 per cent of the heating value of the fuel.

The modern boiler is intricate in design, much of it planned so as to absorb as much heat as is possible before the flue gases are discharged to the stack. Waste heat recovery units have also been introduced in an effort to extract the last possible amount of heat energy from the flue gases.

When smoke stacks are used to create draft in the furnace, a high temperature level in the exit gas is essential in order to produce an adequate draft. Modern practice of exhausting furnaces with fans has removed this requirement.

Uneven Demand. Widely fluctuating demands may require steam boilers or other heat producers to be operated with their output geared to meet maximum requirements. This practice leads to a waste of steam or heat in that with any fuel, even gas, control of heat production in a furnace is bound to be somewhat more sluggish than opening or closing a steam valve leading to a consuming unit. If loads can be scheduled and peak demands anticipated, modern steam plants can operate without appreciable steam loss due to fluctuating demands.

Another solution to this problem lies in an average operation of the furnace, with steam accumulators, or other heat-absorbing units, designed to receive energy during the periods of small demand and release heat when the demand is at a peak. This idea is excellent; its execution is difficult. Heat accumulation means heat storage, and there are currently very few steam accumulators in use which will store even as much heat as can be produced in ten minutes of full-rated steam production in the plant in which they are used.

Boiler Blow-down. Many waters destined for boiler use are contaminated with solid materials in solution. As they are concentrated with the evaporation of the water in the boiler, they

cause many troubles in the operation of the boiler. In order to remove these solids the boiler water must be frequently removed, or "blown down," causing uneven operation and heat loss. The necessity of frequent blow-down can be removed by pretreating the boiler feed water to remove all or most of the troublesome solid substances before the water is fed to the boiler.

Heat Losses. The loss of heat through the walls of the boiler furnace to the atmosphere can be reduced by the proper use of insulating materials. Excessively insulated walls may cause melting of the inside surfaces of refractories.

Losses Due to Mechanical Failure. Losses due to mechanical failure include failures in furnace walls, in boiler tubes, and in drums, and in the connections to the steam distribution system. Furnace wall failure is often caused by frequent boiler shut-downs and consequent cooling and reheating of the walls. This cannot be completely prevented if steam demands do not warrant continuous use. However, extreme caution in cooling and reheating a furnace can reduce the danger of this, and if the boiler is to be out of production because of reduced demand for only a short period of time, it is usually best to maintain a fairly high furnace temperature throughout the "down" period.

Boiler tube failure may cause loss by the release of steam, and loss of production and heat when the boiler has to be cooled for tube repair. Tube failure, other than by direct failure due to uneven stresses, is usually due to overheating, which in turn, is usually the result of an accumulation of solid material (scale) on the inside of the tubes.

Since solids accumulate easily in relatively stagnant pools, boiler designers have designed tube arrangements which eliminate stagnant areas and provide for proper flow of liquids or vapor through the tubes. The accumulation of solid scale is also prevented or minimized by proper feed water treatment.

Reduction of Heat Losses through Walls

Solid walls will retain materials quite satisfactorily, but may allow large heat leakage if the temperatures inside and outside the wall or pipe are greatly different.

Heat-radiating surfaces should be kept to a minimum area to

reduce losses. Heat losses will also be reduced if drafts of cool air are kept away from the walls, and if other cool surfaces are not allowed to remain in close proximity to the hot walls. These are only precautions. Heat loss would be excessive in many installations were it not for the fact that positive heat barriers (insulating materials) have been introduced.

Air is one of the best of all insulating materials. Virtually any material strong enough to support its own weight and in which large amounts of air can be trapped can be considered as an insulator. Insulating material should be capable of being molded, should retain its structure for indefinite periods of time, should not be easily injured mechanically, and must be capable of withstanding any particular conditions, such as condensing moisture or high temperatures, to which it may be subjected.

Both high- and low-temperature insulation is available in the form of loose particles or wool-like materials, precast shapes, and as material which can be applied as a paper and as a plaster. The form of greatest general industrial importance is the precast shape. These may be shaped as bricks or blocks to fit in a flat wall, or as sections designed to fit over pipes or other curved surfaces.

High-temperature insulation is required at times to be dense and strong so it can lend stability to the whole structure, rather than having to be supported by other parts of the wall. Satisfactory insulating material of this kind is made of a composition similar to that used to make other high-temperature (refractory) brick, with varying amounts of wood flour or sawdust added to the mixture from which the brick is made. When the brick is fired, the sawdust is burned out, leaving a light-weight, porous brick which has heat insulating properties, and which will withstand about the same temperatures as the solid fire-brick.

Insulation destined for use in service below the kindling or charring temperature of organic substances may be made of a much wider variety of materials than the insulating brick, magnesia block, or asbestos used in high-temperature work. These are usually cheaper and have superior heat-insulating properties compared to the high-temperature insulating materials. Rock

wool, glass fiber batts, and asbestos paper and boards have wide application in the intermediate temperature ranges.

The cheapest of all such low-temperature insulators is a pulp board or pasteboard. A felt made of flexible paper stock is a close second. Low-density cork board and mineral wool batts are perhaps the best semi-rigid forms of low-temperature insulation, but they are somewhat more expensive than the paper stock. Pure wool also has very good insulating qualities and can be formed into batts or woven into blankets. Many materials are excellent insulators in loose fill, one of the best being kapok, a vegetable fiber.

With proper insulation and construction forming a positive heat barrier, the loss of heat through the walls of a container can be markedly reduced. Molten iron, for example, may be "stored" and transported in well insulated vessels. The vacuum bottle is widely known for its heat retaining qualities, and the storage of liquified oxygen and nitrogen has already been mentioned.

Improved Methods of Heat Use

Conservation of heat energy can be achieved through more complete usage of the energy held in materials such as high-pressure steam. In the ordinary methods of power generation, for example, high-pressure steam is used to turn turbines for the generation of electric power. If there is no other use for the steam, it is condensed as it leaves the turbine and virtually all the heat of vaporization is lost to the cooling water in the condensers.

In the chemical plant it is often quite possible to utilize this heat of vaporization for purposes of heating, either in the chemical processes or in one of the various unit operations. This low-pressure exhaust steam is known as "process steam." It is low in cost because the primary value has been removed in the steam turbine.

An excellent example of the reuse of heat is the steam heated multiple-effect evaporator.

Salvaging Waste Energy

It has been pointed out previously that energy, once released from its latent state in fuels, cannot be easily stored. It cannot,

therefore, be recovered in any large quantity for reuse at any appreciably later time. Heat and energy economics can be effected, however, provided that an absorbing system is available to consume the energy exhausted from an original using system. Heat economizers are widely used for this type of energy conservation.

Exhaust heat in flue gases or waste heat in vapors or liquids is often recovered in ordinary heat exchangers in which the heat in the exhaust is transferred either to a completely different system, or to the incoming cold materials of the same system. These exchangers are the recuperative heaters which have been previously described.

Heat is also reclaimed by passing the hot gases over a relatively cool solid which stores the energy briefly. The heat stored in the solid is in turn given up to a stream of cooler gas. The regenerative heat exchanger, which is an intermittent system, and the pebble heat exchanger, a continuous system, are two examples of this type of operation. They, too, have been described in a previous section.

Heat accumulators are also of some interest. These devices are normally operated as heat economizers, but they may have the dual function of salvaging heat and of developing an increase in heat level.

Either the regenerative or the pebble heat exchanger can be used as a heat accumulator. If a low heating value gas is burned in air, the heat of combustion may not be sufficient to produce the temperatures required. If, however, gas or air, or both, are heated to a high temperature before combustion, the final combustion temperatures may be very high. This is entirely possible with either of these heat exchangers. The unit is started cold, with the low heating value gas and air both cold. They are burned, and the products of combustion passed to the "stoves"; air and gas is heated by heat stored therein on the first cycle. These steps can be repeated until the exchanger reaches the limit set by its resistance to high temperature, or until the combustion space has reached the temperature desired.

A third method of heat recovery is through recirculation. This is actually a reutilization rather than a recovery of heat, since in this operation a portion of the stream of exit material is merely

diverted to the inlet stream and passed with it through the unit. Some advantage is gained in the use of this type of operation in drying materials, as better heat control, improved humidity control, and more satisfactory circulation in the dryer are obtained by mixing waste gas with the fresh gas.

9 : REMOVAL OF HEAT FROM A MATERIAL

Cooling Techniques

By means of a gas

By means of a liquid

By means of a solid

Refrigeration Techniques

Refrigerating media

Mechanical refrigeration systems

It is frequently essential that substances be cooled to prevent reactions prior to the one which is desired (refrigerated or cooled storage), and it is often necessary to remove heat from a reaction in order to control reaction speed and to prevent side reactions which may cause loss of yield and impairment of quality.

Sometimes the problems of heat removal are very difficult. For example, the difference in temperature between most coolants and the system which must be cooled is usually small. Hence, larger surfaces are often required. Higher fluid viscosities are also associated with lower temperatures. This further complicates the problem in the effort which must be made to provide adequate circulation of the mass to be cooled.

The two terms pertaining to the removal of heat from a system are "cooling" and "refrigeration," and while often used synonymously, they ordinarily have a difference in meaning. Cooling generally refers to the removal of heat from a system at temperatures above atmospheric, with the possibility, at least, of lowering the temperatures to those approximating atmospheric. Refrigeration, on the other hand, usually means the reduction of temperatures to levels well below atmospheric.

The first factor in the selection of a technique for the removal of heat from a system is a determination of the final temperature

required. A final temperature above or close to atmospheric may require a cooling operation only; one below atmospheric will require refrigeration or a combination of cooling and refrigeration. Actually the final temperature required, if low, may also be the determining factor in the selection of a type of refrigeration system, in that, as lower temperatures are required, only a very few systems meet the requirements.

A number of factors other than the final temperatures to which the system must be cooled must also be considered in the selection of a cooling or refrigeration system. Some of these factors are:

1. The minimum temperature which can be maintained at the surface of the cooling medium
2. Whether the coolant, either solid or liquid, can be added to the system being cooled
3. Initial temperature of the system being cooled
4. The rate at which heat must be removed. This involves:
 - a. Heat produced
 - b. Rate of heat propagation
 - c. Maximum allowable temperature in the system to be cooled
5. Corrosive qualities of the system or coolant
6. Whether coolant and material in the system to be cooled would react if they came in contact
7. Value of the coolant
8. Fluctuations in demand
9. Temperature and humidity of air
10. Temperature of available water supplies
11. Whether cooling in one system can be used simultaneously with a heating operation in another.

COOLING TECHNIQUES

The heat in materials which are to be cooled is ordinarily removed by a coolant whose temperature is usually raised only a few degrees in the operation. The operation, therefore, involves fairly large quantities of coolant, and usually requires effective

means for countercurrent heat transfer. The two coolants mostly used are air and water.

Cooling by means of a gas (air)

Air is undoubtedly the cheapest coolant. However, its temperature is likely to vary over a wide range from day to night and season to season, and inordinately large volumes are required to remove large amounts of heat. Although air is widely used as a cooling medium, it is not often used at the surface where the heat is actually removed from the system. The more common procedure is to use water as the actual cooling medium and to remove heat from the water by air. However, air coolers and condensers do have limited industrial use.

The direct system obtains the best possible heat transfer, but mixes the air with the substance to be cooled. This may be a serious drawback where the substance being cooled is somewhat volatile and may be carried off as a vapor in the air stream. Where the liquid to be cooled is water, as it often is, this loss of vapor is not serious unless the water is difficult to obtain, or unless it is being carried as a coolant in a mobile unit such as an automobile, where replacement may be difficult. There are also mechanical reasons why even water is sometimes not cooled by direct exposure to air.

Indirect cooling in which the system giving up heat is separated from the air stream by a wall has a much poorer heat transfer rate, but it does avoid the mixing of air or gas with the material being cooled and prevents loss of vapor to the air.

Direct Cooling. Direct air cooling is limited, as has been pointed out, to substances of low volatility or to those like water in which the vapor losses may be ignored.

Cooling of Solids. Solids are nearly always cooled in an air or gas stream. The avoidance of the secondary heat transfer surface in the case of solids is extremely important. The solids to be cooled may be spread in a thin layer and the air blown over, or preferably through, the bed. Blowing air through the material is usually accomplished by spreading the solids on a perforated continuous belt and blowing air through the perforations. Solid materials

can also be cooled by dropping them through an air or gas stream, or by blowing air or gas through or across them as they are agitated.

Materials which dust badly must be handled with as little agitation as possible. One method is to spread the material on a perforated belt and to draw air gently downward through the belt by applying a light vacuum on the underside. Where this method is not feasible, dust separators may be required to collect the solid material picked up by the gas stream.

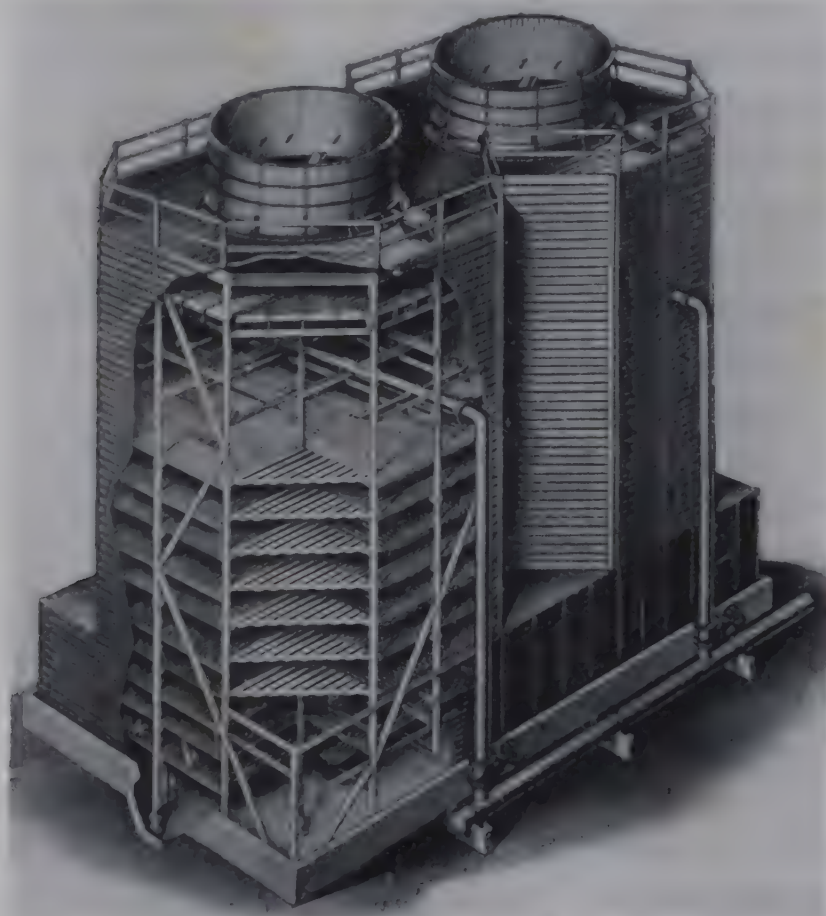
Flammable material must often be cooled by gases other than air. Any inert gas such as nitrogen or carbon dioxide, or sometimes ordinary fuel gases will do. Dry steam is also often used as a coolant to lower temperatures below kindling levels.

Cooling of Liquids. Liquids to be cooled are of two types, non-volatile and volatile. Nonvolatile liquids must be cooled entirely by heat being carried away as sensible heat in the gas stream. The volatile liquids are cooled by removal of heat as sensible heat of the gas stream, plus the cooling effect produced by the vaporization of the liquid. The final temperature of the liquid may be well below the actual temperature of the gas stream. In this case, both the temperature of the gas stream and the relative saturation of the vapor contained in it are important factors. The equipment necessary to effect this type of cooling operation is simply that required to bring large volumes of gas into intimate contact with the liquid to be cooled. Much of this equipment is used for liquid-gas mixing and is described in the section under mixing techniques. There are, however, several kinds of apparatus used for cooling water which are more or less unique to this operation and are, therefore, appropriately described in this section.

An exceedingly low cost method of cooling water, where space is not expensive and water is plentiful, is in open ponds or *lakes*. Two or three acres of open water will dissipate a large quantity of heat. Ten to fifteen acres will suffice for almost any cooling requirements which any one plant might have. Such lakes have been worked into the landscaping of some plants to the enjoyment of the workmen and the profit of the plant.

There are some difficulties in the use of lake water for cooling, however. An earthen-bottom reservoir is difficult to keep free of

algae and other slime-forming microorganisms. Further, there is always the problem of bird feathers and droppings. Such lakes, even in northern climates, may remain relatively free of ice, and hence are a strong attraction for migrant waterfowl. Such water will also carry a certain amount of suspended sand which may cause trouble in the circulating pumps and cooling system. Never-



(The Fluor Corp.)

Figure 56. Grid Cooler; Induced draft (Sectionalized view).

theless, this is a low cost and desirable cooling system for water which is to be continuously recycled in the process.

Lakes used for cooling water are usually connected in pairs, with warm water being introduced at one side of the first lake and having to traverse both this lake and the second lake to reach the cooling water pump intake.

Another system, widely used in areas where there is a fairly steady movement of air, is the *spray pond*, in which the water is cooled by spraying it into the atmosphere through nozzles very

similar to those used in lawn sprinklers. The cooled water collects in a concrete lined basin beneath the sprinklers. This system, satisfactory if there is some movement of air, may be quite ineffective on a quiet, humid day. Considerable loss of water is experienced in even medium wind velocities. The costs of installing the system and of operating the circulating pumps are items of considerable magnitude.

Other devices for bringing air and warm water in contact are the *grid tower* and *cascade-type coolers*. In these coolers the water flows gently out of pipes laid along the top of the tower, in which wooden slats are positioned so as to course water over their surface and discharge it to other wooden slats located in the next lower level. Air is given free passage between the slats.

This unit has about the same faults as the spray cooler, except that power requirements are likely to be lower, and wind does not so easily blow away the water. It can also be built higher so it does not require as much area for installation. Maintenance will probably be no higher than for the spray pond, and initial cost is reasonable.

Both the cooling tower and the spray pond are ineffective coolers without adequate air movement. Hence, the most up-to-date cooling tower installations usually provide fans to move the air through the tower.

Cooling of Gases. The cooling of a heated gas by direct contact with a coolant gas such as air is seldom practiced, unless a mixture of the two, at some intermediate temperature, is to be used in further processing.

Indirect Cooling by Air or Gas. Where volatile or inflammable liquids are to be handled, or where water is to be retained within the cooling system, cooling by air may be accomplished in air-cooled heat exchangers. Liquids, like cooling water in the automobile motor, are often used as coolants in heat exchangers or in the jackets of reaction vessels, and are themselves cooled in air-cooled heat exchangers. This is nearly always more satisfactory than the use of air directly as a coolant on the initial heated surface. There are exceptions to this rule.

Here, as in nearly every case involving the transfer of heat between a metal surface and a gas stream, the metal surfaces will

give greater heat transfer if they are deeply finned. In most industrial cooling systems, as in the automobile radiator, for efficient operation, the air must be given positive motion over the radiating surfaces by means of a fan.

Cooling by Means of a Liquid

Liquids, like gases, can be used as coolants either in direct contact with the material being cooled, or by extracting the heat through the walls of a heat exchanger. Direct cooling is the most rapid and most efficient, but the liquid mixes with the material being cooled. Liquids are, however, used for direct cooling of solids, other liquids, both soluble and insoluble in the coolant, and gases. Indirect (heat exchanger) systems are the most widely used, for in spite of their lower efficiency, it is usually highly desirable to keep the coolant liquid separate from the system giving up the heat.

Direct Cooling. The direct cooling of materials by means of a liquid is limited to those cases in which the liquid will not harm the material being cooled. It should be easy to separate the coolant from the material or permissible to leave the two together. The latter condition generally indicates that neither the coolant nor the material being cooled has any appreciable value.

Cooling of Solids. Many solid materials can be cooled effectively by quenching in a liquid medium. Extremely rapid cooling is one of the most desirable features of this technique.

Since heat capacities of many liquids are relatively high compared to most solids, not only will heat transfer be rapid, but the final temperature reached may be fairly easily regulated by adjustments in the initial temperature of the coolant liquid. In addition to water, liquids such as brine solutions, petroleum oils, various organic liquids, and molten solids such as salt and lead are used as coolants.

The rapid quenching of solid materials like certain slags may help to shatter them and reduce the amount of subsequent grinding necessary to convert them into fine dusts. This is the opposite effect to that desired in the quenching of coke, where every precaution is taken so as not to destroy the coke structure. Controlled

cooling may be employed to develop or retain special iron and iron alloy structures.

Cooling of Liquids. The cooling of a liquid by direct contact with another liquid is not often practiced, except in one outstanding example. This is the use of water sprays in contact condensers normally used in conjunction with steam jet ejectors. The water condenses water vapor emerging from vacuum evaporators and cools the resultant condensate water. In this case the vapor has no more value than does the cooling water, and both can leave the condenser together.

It is also possible to use a water spray as a coolant for condensing or cooling materials such as hydrocarbon vapors or liquids insoluble in the water. This is not often done because of subsequent problems of separation.

Cooling of Gases. The cooling of gases by contact with a cool liquid is a perfectly sound procedure, providing, of course, that the gases are insoluble in the liquid, or that both the dissolved gas and the coolant liquid can be used or discarded together. The techniques employed are very similar to those used for cooling a liquid by means of a cool gas. Any device in which intimate contact of gas and liquid can be effected is suitable for this purpose.

Indirect Cooling. The use of liquid coolants in standard heat exchangers or in the coils or the jackets of reaction vessels is widespread. Cool water is often sprayed over warm surfaces of tanks, or over open coils. Solids are also sometimes cooled by being spread in a thin layer on a metal conveyor belt which is, in turn, cooled from underneath by water.

Precautions must be taken to make sure that the coolant does not bypass a large part of the transfer surface. Unless inlet and outlet pipes are located some distance apart, unless there is some way to vent gas from the jacket of heat exchangers, and unless there is some means of making certain that the heat exchanger or water jacket is completely filled with the cooling medium, very unsatisfactory results may be obtained. Even water sprayed on tank surfaces easily collects into rivulets, leaving large areas of tank surface uncooled. Securing proper distribution and contact is likely to be a serious problem.

The heat exchangers used for cooling or condensing are exactly

the same as those used for transferring heat to a reaction space. They have been described in a previous chapter.

Cooling by Means of a Solid

Cooling of liquids or gases by the use of solid materials is perfectly possible. The solids would simply have to be used in the regenerative or pebble heating units. Because of the difficulty in handling solids, and because of their rather low heat capacity they are rarely used primarily as coolants.

REFRIGERATION TECHNIQUES

Materials can be cooled to temperatures appreciably below normal atmospheric temperatures by contact with ice. They can also be refrigerated, either as a primary or secondary step, by the expansion of a highly compressed gas (Joule-Thomson effect), or by the evaporation of a liquid which can be made to vaporize at a temperature near the cold temperature required.

As was the case in the propagation of heat and its transfer to an absorbing system by steam or heated liquids, refrigeration is most often transferred first from the refrigerating plant to a body of water or a brine solution which, in turn, is circulated through the heat exchangers where the refrigeration is required.

Ice, refrigerated brine, and solid carbon dioxide are the primary refrigerating agents. Each of these has a fairly specific field of use in absorbing heat.

Refrigerating Media

Ice was at one time the only refrigeration medium. Natural ice can be harvested from the lakes and rivers of the northern half of the country during the winter months and stored with reasonable ease and at low cost. When properly bedded in straw or sawdust, ice has remarkable keeping qualities. Ice at one time was even shipped considerable distances.

Mechanical refrigeration has made ice-making independent of climatic conditions. Some natural ice is still cut and stored where warehousing is still available, and when weather almost guarantees a reasonable harvest. This natural ice is often used for icing

railroad refrigeration cars, fishing boats, and sometimes for industrial purposes. However, the greater purity of manufactured ice made from ordinary domestic water makes it a much more valuable commodity.

Ice is a reasonably good refrigerant since it absorbs at least 144 Btu per pound (its heat of fusion). It can be stored in large quantities and with little storage loss, so that it can meet fluctuating cooling demands. It is, however, fairly costly to make and requires considerable labor to transport and use. Further, the minimum temperature usually obtained is about 32°F, although it can be melted in a brine solution to produce temperatures of 0°F or below.

As a solid it is rather difficult to use, since heat cannot be transferred readily to it unless it is suspended in a liquid. The latter course is sometimes followed as, for example, in the cooling of certain organic reactions. Here the rapid cooling which is possible through the addition of chipped ice is desired, and the resultant water can be separated readily from the products. If it is to be used as an indirect refrigerant, it is often necessary for it to be floated in water or brine, and the ice-cooled liquid circulated to the walls of the heat exchanger.

Solid carbon dioxide has many of the same advantages and disadvantages as ice. The temperatures obtained with solid carbon dioxide are much lower than can be secured with ice. The product of this coolant is gaseous and in most cases is more readily removed from a system than is the water resulting from the melting of ice. It has a fairly high capacity for absorbing heat and has good keeping qualities. It is several times as costly as ice, and is employed as a refrigerant only when others cannot be easily used.

Refrigerated Brines. Calcium chloride dissolved in water produces solutions having freezing points as low as -40°F. Its low cost and generally excellent properties in solution make it very useful as a brine for refrigeration purposes. Sodium chloride gives equally good results at similar costs at temperatures above -6°F.

The brine is cooled by a mechanical refrigerating system, is then stored if necessary, and is finally circulated to the heat exchangers of the system which is giving up heat. Even ice is frozen by circulating brine through the freezing tanks rather than by direct con-

tact of the water with any part of the mechanical refrigerating system.

The use of brine requires the installation of circulating pumps, storage tanks and distributing pipes, and gives rise to all the corrosion problems which are entailed in handling a salt solution in a metal system. However, it has so many advantages that these difficulties are minimized.

Since brine is a liquid, it is easier and cheaper to handle than ice; it is a more effective heat transfer agent; and it will maintain lower temperatures than can normally be obtained with ice. It cannot be easily stored for an extended time.

There are several other reasons for circulating refrigerated brine rather than using the cold coils of the refrigerator itself as the heat-transfer surface. The coils of the refrigerating system are set to operate at a uniform temperature, whereas the brine can be maintained at any temperature between the coil temperature and room temperature. It is easier to store brine to take up fluctuating demands than to require the refrigeration plant to stop and start periodically. Brine is cheaper than the refrigerants used in the plant; hence it is more economical to refrigerate brine in a compact plant and then circulate the chilled brine, than it would be to supply the primary refrigerant through an extensive cooling system. Finally, refrigerating systems often contain ammonia, sulfur dioxide, or other materials as refrigerants, which might be obnoxious or even dangerous if accidentally released in a plant. By restricting these entirely to the refrigerating plant, the danger of their accidental release in a main manufacturing plant is nil.

The use of direct refrigeration is limited to those situations where refrigeration requirements are small and the added expense of brine circulation is not justified, where the whole system can be made a compact unit, and where demand is reasonably uniform.

Mechanical Refrigeration Systems

Of the several possible types of mechanical refrigerating systems, those using vaporizing liquids are the most important. Very low temperatures can be best secured by the expansion of a gas.

Refrigeration by Vaporization of Liquid. If any liquid, such as alcohol, ether, or other liquid which volatilizes readily is poured on an exposed surface, it will vaporize rapidly. As it vaporizes, it develops a temperature approximating its wet bulb temperature, which, if the vapor is removed from the space above the liquid, may be well under the actual ambient temperature. Any system which can supply an easily volatilized liquid and can withdraw the vapor as it is formed provides the basic elements of this type of refrigerating system.

Compression Systems. The compression system is the most important of several which operate with vaporizing liquids as the refrigerant. There are two general compression systems in use: mechanical compression and jet compression. The first is the more useful since it is completely cyclic in nature and can use any one of the many commercial refrigerants which have been developed. These refrigerants will allow much lower temperatures to be obtained than can be secured through the use of water as a refrigerant, water being the one material inexpensive enough to be used in the jet system.

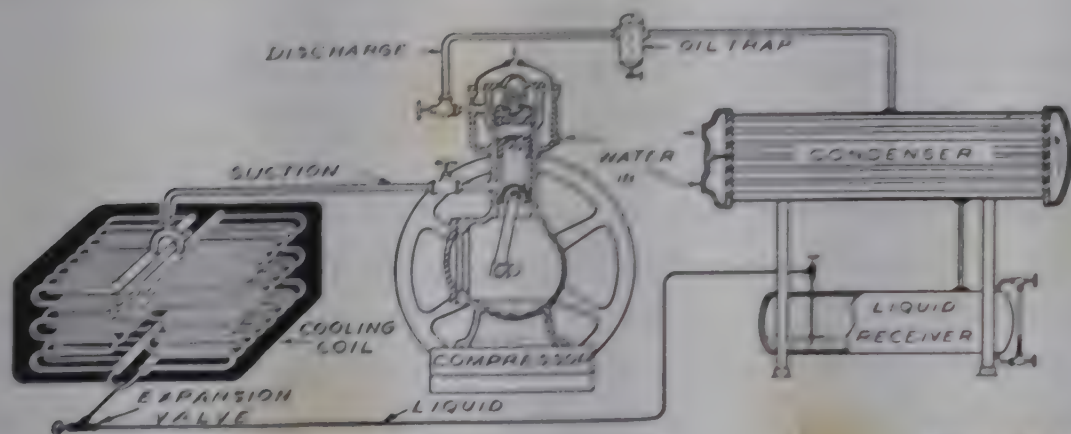
The mechanical compression system operates in a thermodynamic cycle of several steps. These steps are as follows: (a) Vapor of a low-boiling liquid (refrigerant) is compressed in a mechanical compressor. In this operation heat is developed and the temperature of the vapor rises. (b) The warm vapor is passed to water or air-cooled heat exchangers where the vapor is cooled, and since it is under sufficiently high pressure, it is condensed. (c) The condensed liquid is led to an expansion valve through which it is expanded into the cooling coils (expansion chamber). (d) The liquid is vaporized in the cooling coils, absorbing heat as the vaporization takes place. (e) The vapor is removed from the cooling coils, and recompressed as step (a) in a new cycle.

Commercial systems usually use either a reciprocating or a centrifugal refrigeration compressor; small to medium plants nearly always use the reciprocating type, larger installations often use the centrifugal compressor. The rotary compressor is also used to a limited extent in commercial practice.

A refrigerant used in a mechanical system should possess certain properties. For example, it should be low in cost, be stable

chemically, have the correct vapor pressure, be inert to metals, be nontoxic and nonflammable, be easy to detect in case of leaks, and should not attack lubricants. A number of refrigerants are available, no one of which, unfortunately, has all the desirable properties. "Freon," the name of a group of fluorinated hydrocarbons, is superior as a class to any other refrigerant except in the matter of cost. They are all expensive, but are nontoxic, nonflammable, and quite inert.

Ammonia was one of the first refrigerants and is still used widely. Its low cost and the ease of detecting leaks are two factors in its favor. Its toxic character prevents its use in marine refrigeration, in air conditioning, or in other installations where leaks might create dangerously toxic gas concentrations.



(Frick Co.)

Figure 57. Compression Refrigeration Cycle.

Sulfur dioxide is also much used in household refrigeration, and several of the chlorinated hydrocarbons find application in air conditioning. Substances such as carbon dioxide, propane, butane, ethane, methyl bromide, carbon tetrachloride, ether, and many others have limited use as refrigerants.

The *jet compression system* operates by evaporating water under a high vacuum. As the water evaporates, it is cooled. The only vacuum pump capable of handling the volume of vapor produced in this operation is the steam jet ejector. This system is simple, fool-proof, and reasonably cheap. The main difficulty is that the minimum temperature which can be reached is about 40°F.

Absorption Systems. The absorption system of refrigeration is of small industrial importance. It is unusually novel in its application of physical principles.

This is the system used in the Servel Electrolux domestic refrigerator (Planters Munten System). It is of interest because it is quiet in operation, and can be operated using a gas or kerosene burner and hence is not dependent on electric power. It is satisfactory for low temperature work, which gives it some industrial significance. The absorption system has the disadvantage of being bulky, and it is rather inflexible in operation. The larger units may require close attention.

The absorption system operates on a regular cycle. The steps are as follows: (a) The refrigerant, usually ammonia, is drawn from the expansion coils at a given pressure in a stream of inert gas such as hydrogen. (b) The gas and refrigerant vapor are passed to an absorber where, at a pressure somewhat less than that at which it exists in the cooling coils, the ammonia is dissolved in cold water. (c) The ammonia solution is freed of ammonia by heating it in a generator. The water is sent first to a cooler and then back to the absorber. (d) The ammonia is passed to a rectifier where it is freed from entrained water. This water is then cycled back to the generator. (e) The gaseous ammonia, now pure, can be liquefied by passing it to a condenser. It is collected in a liquid receiver and is returned as needed to the cooling coils where it is re-evaporated into the hydrogen stream, thus completing the cycle.

The Servel system creates all circulation by hydrostatic forces within the system. Commercial units normally employ pumps for circulation.

Refrigeration by the Expansion of Gases. A number of refrigerating systems have been devised, varying considerably in style and design, but all utilizing the Joule-Thomson effect—the phenomenon of a gas being cooled by expansion.

If a gas is compressed, cooled, and then allowed to expand, it is chilled in the process. While the processes are not important for refrigeration purposes, they provide a means of producing the low temperatures required for liquefying air and the other so-called fixed gases.

One of the first successful commercial processes for liquefying air was developed by Linde. In this process a mechanical compression refrigerator first cools the compressed gas to -40°F , the remainder of the cooling being obtained by the expansion of gas. Pressures of 100 to 200 atmospheres are used in the gas system.

Most of the later commercial systems for air liquefaction are much more complex than the original Linde process, but all operate on the same general principle.

SECTION IV

CONDITIONS AFFECTING THE CHEMICAL REACTION

10 : MEASURING AND PROPORTIONING MATERIALS

Quantity Measurement of Solids

- By weight

- By volume

Proportioning Solids (feed control)

- By weight

- By volume

- Determination of concentration

Quantity Measurement of Liquids

- By weight

- By volume

Proportioning Liquids

- By weight

- By volume

Quantity Measurement of Gases

Proportioning Gases

Many chemical reactions are exceedingly sensitive to the concentration of reactants. The addition of incorrect amounts of reactants may cause the reaction to progress with little or no control, and may give poor yield and quality of end products. Chemicals may also be wasted by improper proportioning, and the problems of separation and purification may be magnified by the addition of incorrect initial amounts of reactants. Therefore, plant operating instructions frequently include explicit directions relating both to the total quantity of materials to be added to a reaction mass, and the schedule of their addition.

The measurement of material quantities has highly important applications in most chemical factories other than its use in connection with feeding, proportioning, and controlling addition of reactants. These measurements can be made to furnish figures relating to the receipt of raw materials; the quantity of materials in storage; the transfer of materials from department to depart-

ment, or from one operation to another, with the consequent possibility of a continuous check on production efficiencies in each operation; the scheduling of production and work hours; the packaging of materials in units of uniform size; and the shipment of material from the plant.

This general subject encompasses weighing and metering, flow control, proportioning, sampling, determination of concentration, and chemical analysis.

The factors influencing the choice of a technique for weighing or metering, or for control of the addition of materials to a reaction space are similar, in general, to those governing the choice of other methods. They include such items as:

1. Nature of material to be added
 - a. Solid (dry lumps, powdered material, sticky, hot, cold, density, particle size and size range)
 - b. Liquid (corrosive character, vapor pressure, temperature, viscosity)
 - c. Gas (pressure, temperature)
2. Quantity to be added
 - a. Total
 - b. Amount per unit of time
3. Accuracy required
4. Addition schedule
5. Whether material exists in batches and is to be measured and added, or both, in that form, or whether it must be measured in a continuous stream
6. Ease with which results can be converted from volume to weight or vice-versa.

QUANTITY MEASUREMENT OF SOLIDS

The techniques available for measuring the quantity of solids introduced into a reaction space, or for measurements relating to purchasing or selling data, involve the determination of either weight or volume. The measurements may also involve determinations of solids concentrations.

Measurement of Solids by Weight

The measurement of quantities of solids by weighing is the most positive and accurate technique available. Weighing equip-

ment is made which will weigh either batchwise or continuously. Batch weighing of material is carried out with the least expensive types of weighing equipment and certainly with the most foolproof. However, when material must be fed continuously to a system, the batchwise character of this procedure may impose some difficulties. The fluctuations can be leveled out somewhat by weighing in smaller batches at more frequent intervals. Some operations will feed from intermediate storage bins, or reasonably uniform feed can be achieved by weighing on two or more scales, the hopper or container of one being discharged while that of the other is being refilled and weighed.

Presuming that a bin or hopper is used to hold a granular solid, the weight of material it contains can be obtained by two different methods. In one method the hopper or bin is filled and the contents weighed, the weight being manually or automatically recorded. In the other method the scale is set to trip at some given weight, so that when this weight of material has been charged into the hopper, the feed to the hopper is automatically closed and a uniform amount of material per batch is obtained. In this operation the only records necessary are the weight setting and the total number of times the hopper has been refilled. To activate the tripping mechanism the scale beam may be provided with electrical contacts; or the dial of the pendulum scale may have movable contacts which close a circuit when the beam is balanced, or a photoelectric stop activated by the indicator when it passes a given weight. The amount of material per batch can be changed at will by changing the weights on the scale beam or the location of the cutoff on the dial scale.

Devices are also available which can be arranged to give a continuous indication of weights of material passing over them on moving belts. The device is simply an ordinary scale having a reasonably large platform, across the surface of which a belt carrying the solid can be moved. Idling rollers attached to the scale platform support the belt as it passes across the platform. This scale indicates instantaneous weights as material travels on the conveyor, and without auxiliary devices gives only a continuous weight check. To make the scale record total weight of material passed in any unit of time, an integrating mechanism which continuously multiplies weight by belt speed must be installed.

Measurement of Solids by Volume

When the moisture content of a solid material varies considerably, the weight of material has little value in accounting for an actual amount involved in an operation. There are also situations in which scales are not conveniently available, and yet in which it is necessary to make a quantity determination. In such cases, an approximation by volume may be far better than no measurement at all. Actually, the quantity of granular material per unit of loose volume may be remarkably uniform.

Measurement of volume may be batchwise or continuous. Batch measurements may be independently made; continuous measurements are usually made in connection with the feed of material to a reaction mass. The batch-wise measurement of solid volume is accomplished either by the estimation of volume of an existing pile of material, by delivering material to a hopper or other container and measuring its height in the container, or by filling the container to some pre-determined level. The last method is most frequently used.

There are several devices available for indicating the location of the level of loose solids in a bin. One of these consists of a flexible diaphragm mounted in the side of a bin; another is a compressible button attached to an inside wall. Either of these will be activated when solid material settles against it, and can be used to shut off filling mechanisms and to indicate level. Another type of indicator alternately lifts and lowers a weight on a cable. Slackness in the cable as the weight is lowered operates an electric signal which indicates the level of solid in the bin. A third method employs a small paddle turned by a motor suspended by a loose hanger. When the solids rise high enough in the bin to engage the paddle, the paddle stops, the motor turns on its support and breaks the electrical circuit, stopping the motor and activating gates or other devices associated with filling or emptying the bin.

Most of the methods designed for continuous volume measurement of solids are associated with feeding devices. The use of the screw conveyor as a feeding device has been mentioned. This conveyor will deliver a rather accurate volume of solids with each revolution. The rate of delivery can be varied at will by changing

the speed. The bucket elevator is also a quite accurate measuring device for solid materials, providing the loading boot is kept filled with granular material. Even well-filled flight conveyors of certain types can be depended upon to deliver a fairly accurate volume of solid material. A simple calculation involving cross-section and speed will give data on delivery.

PROPORTIONING SOLIDS

The most positive means of controlling the addition of solids to a reaction mass involves filling a container, weighing or estimating the volume, and then introducing the solids by discharging the containers at regular time intervals. Continuous conveyors are somewhat less accurate but quite satisfactory for many proportioning requirements. Most proportioning and feeding devices have been designed for some specialized proportioning problem.

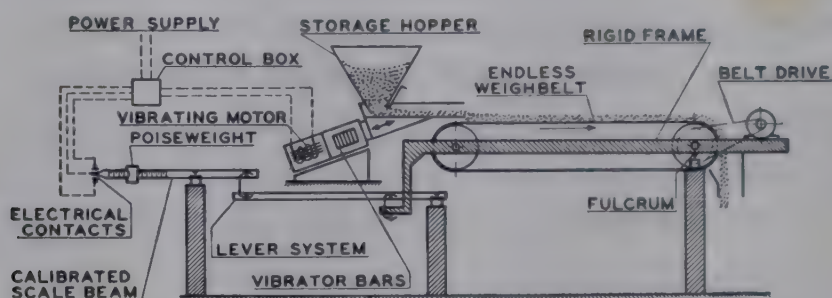
Proportioning Solids by Weight

Devices for proportioning, like those designed for weighing only, are available for either batch-type or continuous addition of material. Like the weighing devices, the batch feeders are likely to be more accurate, more fool proof in operation, and cheaper to install than are the continuous proportioners. The main difficulty in the use of batch feeders is that there is no way in which to prevent some fluctuation in the feed rate.

The *weigh hopper*, fitted with a discharge chute, can be used as a feeding device. If filling is reasonably rapid and the rate of use somewhat slow, there may be an inconsequential time interval between the end of a delivery of one batch and the start of the next. If the fluctuation is serious it can be leveled off by using two or more weighing hoppers arranged in parallel. These can be made completely automatic if necessary, or they can be arranged to drop a weighed charge into a second receiving bin from which material can be moved in a continuous stream to the reaction mass.

Weight feeders arranged for continuous operation are usually of two common types, the pivoted-belt feeder, and the loss-in-weight type. The *pivoted-belt feeder* is made up of a hopper fitted with a sliding gate through which material is fed to a moving

pivoted belt. As it leaves the hopper, the material activates the gate, the opening of which varies with the amount of material passing through it. The motion of the gate is integrated mechanically or electrically to give a measure of the weight of material passing from the feeder. Regulation of the feed rate may be achieved by changing the position of the belt counterpoise, or by increasing or decreasing the belt speed. The first arrangement is satisfactory for most purposes and is cheaper than the speed-changing mechanism.



(The Jeffrey Mfg. Co.)

Figure 58. Vibrating Weigh Feeder. Pivoted belt.

The *loss-in-weight feeder* consists of a hopper suspended from scale levers. The scale beam has an electrically driven counterpoise which activates the discharge opening. The counterpoise moves along the beam at a set rate, continually unbalancing the beam. Material is fed from the hopper at a rate to compensate for the unbalance. The main difficulty with this type of feeder is that the unit must be shut down while the hopper is refilled.

None of the various weigh feeders is a scale, although they can be and often are used for work requiring rather critical adjustment of solid weights. None of them weighs and then feeds; they feed first and then check and adjust the weight of further feeding through weights of material already passed.

Proportioning Solids by Volume

The control of the feed of solid materials by volume is an operation much more easily accomplished than are any of those used for feeding by weight. Where accuracy of weight proportioning is essential, the weighing mechanism, if a hopper or bin,

is often discharged into a second receiving hopper from which the material is actually fed by means of one of the several volumetric proportioning devices. Since solid materials vary so greatly in character, many feeder types have been devised for solids handling.

For intermittent operations, batch proportioners are usually quite satisfactory; and since they are likely to be simpler and cheaper than continuous proportioners they are much used where conditions are favorable. Batch proportioning is frequently used in conjunction with those continuous operations where temporary variations in concentration have little effect.

Batch proportioning usually involves the use of a shovel, wheelbarrow, or an overhead tank or bin, filling this to the proper level with the material to be fed to the operation, and throwing or dumping the contents into the reactor. A widely used expedient of batch proportioning is to fill the reaction vessel itself to predetermined levels with the materials to be added to the process.

A number of different devices are used under various conditions for the continuous feeding of bulk solid materials to an operation. All feeding units consist of a hopper or bin and a device for delivering the material at a predetermined rate from the bottom of the hopper. It is in the delivery system where the major variations occur.

The several conveyors, such as the screw conveyor, flight conveyor, apron conveyor, bucket carrier, and even the belt conveyor have all been used as feed devices leading from the bottom of feed bins. The screw conveyor is probably most accurate and satisfactory for this purpose. Most conveyors can often serve the dual function of conveyor and feeder.

In addition, there are a number of devices designed specifically for delivering solid materials at a controlled rate from the bottom of a bin. There are several types of gate feeders which control the size of an opening in the bin outlet; there are also roll feeders, disk feeders, and rotating vane feeders which govern the delivery rate by the speed at which they turn; and shaking, vibrating, chain drag, plunger, and swinging gate feeders. Some of these have rather specific fields of application, but often several different

kinds of feeder will give satisfactory service on the same material and under the same circumstances.

One of the most troublesome features of handling solid material from a hopper into a feeding device is the tendency of many solids to arch inside the bin above the discharge opening and resist extensive efforts to break them down. Not only is delivery interrupted, but accuracy of feeding is nearly always impaired when the feed device is not continuously filled with material from the hopper.

Arching varies with the nature of the material being handled and with the shape and general construction features of the bin. Interior bracing, such as tie rods, banding and ledges, may create the worst possible conditions and should be avoided. Conical hoppers and circular bins are preferable to square bins. One method of breaking up arching material is to attach one or more electric vibrators to the sides of the hopper. Another is to use a double-walled bin, the inner wall capable of being flexed by compressed air. Air jets located near the bottom of the bin have sometimes proved effective. In small hoppers or with light materials, mechanical agitators have been used with good results. Louvers or poke holes are often placed in the lower walls of hoppers to provide access for bars. The bottom cone or pyramid of the hopper should have as steep walls as possible, and should never have an inclination less than the angle of repose of the material being fed. The discharge opening must be at least three times the size of the largest lump. Occasionally material may be so sticky or have such a tendency to arch that the bin must have vertical sides, and the feeding devices must provide a complete live bottom for the bin. This is not hard to do with apron or belt feeders, and it can be done with screw feeders by placing several of them in parallel in the bottom of the bin. This may, however, eliminate the possibility of using many of the feeding devices.

Determination of Concentration

The proportioning of solid material has little significance in many situations unless the moisture content or the purity or concentration of an active ingredient is known. Further, propor-

tioning of solids by volume almost always necessitates a determination of apparent density. These items are not often given consideration because their determination is more likely to be a laboratory than a plant problem. Nevertheless, plant operation is so completely dependent on accurate information relating to material quantities, and the quantities so often involve laboratory determinations, that the plant operator cannot afford to permit these results to be meaningless because he is unfamiliar with the methods of their determination.

Sampling. No determination, regardless of the accuracy with which it may be completed in the laboratory, is any more representative of actual concentrations than the sample on which it is run. The analysis of poor or nonrepresentative samples may be far more serious than a lack of fourth-place accuracy in the analysis. The size of a sample varies both with the quantity being sampled and the anticipated maximum variation within the mass of material. This quantity has been carefully determined in connection with many of the more common materials by means of statistical analysis, and by careful checking of the variations observed.

Sampling from Stationary Piles. Sampling of large piles of material is usually quite difficult because the properties of the material on the outside of the pile, which is exposed to the atmosphere, may be quite different from the properties of the material in the interior of the pile. Furthermore, properties may be changed by the length of time material is stored and may, for this reason, vary considerably from the top to the bottom of the pile. In sampling coarse solids from a pile, open freight cars, or bins, shovelfuls of material are taken from the mass at regularly spaced intervals. These intervals may be most conveniently laid out by using a rope which has had knots tied in it at predetermined intervals. Where it is likely that surface material is not representative of the entire mass, sampling should be carried out only after the outside of the pile has been removed. When the material is fine, and flows easily, like grain, sampling can be accomplished by thrusting a pipe into the pile. The pipe is arranged so that holes in the side of the pipe can be exposed after it has been inserted. The grain which flows into the pipe is

prevented by a mechanical trap from falling out as the pipe is removed.

Sampling from a Moving Conveyor. It is usually much simpler to take an accurate composite sample from a moving belt or other conveyor device than from a stationary mass of the material. Grab-sampling by means of a shovel is common practice. The sampling should be done at regular intervals and often enough to assure that an adequate and accurate total sample is secured.

Mechanical samplers are often employed. These not only eliminate the expense of the labor required in hand-sampling but assure a sample which is free from the element of choice. Mechanical sampling devices are to be recommended in every case in which they can possibly be employed. There are scores of different kinds of mechanical samplers. Many are provided with dippers or scoops which dip into the moving stream at time intervals held constant by motor and gear drives. Others are arranged to cut a small segment continuously from the larger stream of material passing the sampling point. The selection of any one of these will usually depend directly on such items as cost, location, and ease of installation.

Sample Preparation and Treatment. Most samples when taken are far too large to be used as such for analytical work. They must, therefore, be reduced in size without destroying their uniformity. This involves a repetition of three required steps: (1) reducing the particle size; (2) thorough mixing; and (3) separating the sample into segments, only a portion of which are retained.

Caution must be always observed in the use of any mechanical sampling equipment, to be sure that all material from previous sampling, mixing, crushing or other operations is thoroughly cleaned from the equipment so as to avoid contamination of a new sample by an old one. Other avenues of contamination must always be closely observed, so that materials are not added to the sample from external sources during the sampling or the several preparative steps.

If the sample has appreciable moisture which is readily given off to the atmosphere, or if it absorbs moisture, air, or other gases

from its surroundings it must be reduced rapidly and stored in closed containers. Sample reduction must also be accomplished without generation of heat. The laboratory sample should be tested as promptly as facilities permit.

Chemical Analysis. The development of analytical data relating to purity, concentration, quality, and the general ability of the material to meet specifications usually is the task of highly skilled chemical technicians, and the design or production engineer must be guided by the results released by the laboratory.

QUANTITY MEASUREMENT OF LIQUIDS

It is decidedly easier to measure and regulate the flow of liquids than that of solids. The techniques available are numerous, highly varied in character, and are adaptable to a wide range of requirements. Liquids can be measured either by volume or by weight and in batch or continuous systems.

Measuring Liquids by Weight

Although it is frequently desired to have the weights of liquids so that results can be recorded on that basis, the relatively easier operation involved in measuring liquids by volume and the facility with which liquid densities can be determined discourage weight measurements. There are relatively few examples of measurement of liquids by weight. These, for the most part, deal only with those like liquid chlorine, which must be kept under pressure, are highly corrosive, or have other properties which make volume metering unsatisfactory.

The liquid *weigh tank* is fairly common to chemical industry. This is simply a tank of the size required to hold the batch of material and of such construction and design that it can be mounted on a scale platform. Liquids can then be weighed into the tank, or out, or both.

Difficulties of construction of equipment for continuous weight measurement and the speed, ease, and accuracy by which liquids can be measured by volume discourage the use of devices for weighing liquids in a continuous stream. A rather primitive device for the continuous metering of liquids by weight—the tilting box—has been used, but it is of interest only as a historic

item. The condensate meter, a more up-to-date version of the tilting box, has some use. This meter operates by driving buckets on a rotating spider.

Measuring Liquids by Volume

There are scores of different types of instruments available for this measurement, and the selection of the best type for a specific application is often almost impossible; it is frequently not necessary, since several may be equally satisfactory.

Batch Volume Measurement of Liquids. The measurement of liquids in a static mass is certainly fundamental, and is encountered somewhere in every process industry serving as a check on inventories, for measuring a definite quantity of liquid into a process, or as a primary means of production control.

Direct Liquid-level Indicators

Batch measurement of liquids normally means the measurement of liquid level in a tank. The tank may be open or closed, under pressure, or at a high temperature, or it may be filled with corrosive liquids, but under almost any set of circumstances, there is some liquid-level indicator which will give satisfactory results.

Liquid level may be measured either directly or by so-called "inferential" methods which measure some variable easily translated into a liquid-level reading. The *gage stick* is the simplest of all direct liquid-level indicators. It may take the form of a portable calibrated stick, or it may appear as figures inscribed on the inside of a tank, either on the tank wall or on a pole fixed within the tank. The main disadvantages of the gage stick are that it is indicating only and cannot be made recording, and that it usually requires some manual operation to obtain results. Balanced against these are its low cost, reliability, and general convenience.

The *gage glass*, through which the liquid level can be read directly, is of greater convenience in many cases, although of greater cost than the gage stick. The tank on which it is used must be drilled to permit its installation. Its use does not, how-

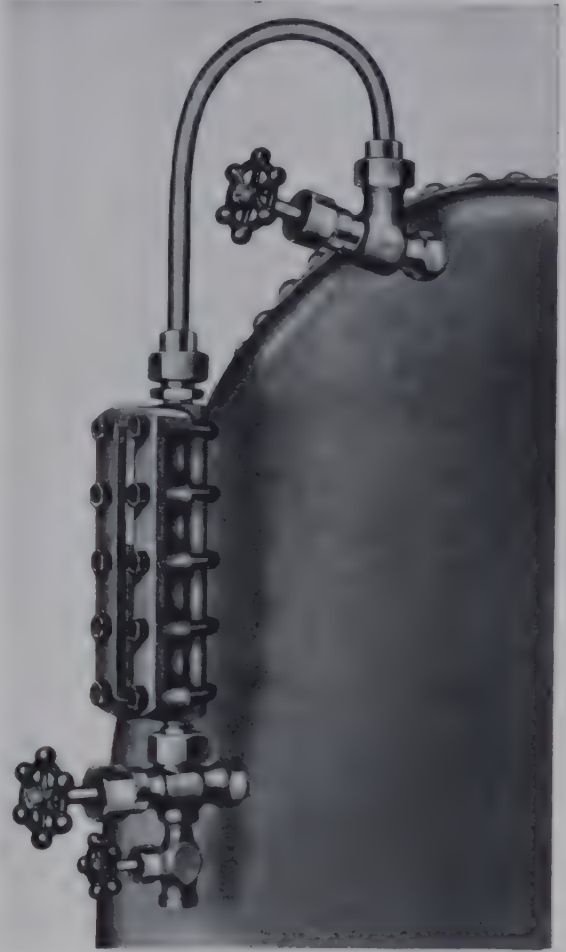
ever, require the opening and closing of a tank; thus it can be used on tanks under moderate pressure. In addition to its higher price and installation costs, the gage glass may become coated on the inside with an opaque film when used with certain liquids. There is also the ever-present danger of breakage, and the occurrence of leaks if and when tubes break. The gage glass is indicating only. It cannot be read from a distance.

A low-density solid or a hollow sphere floating on the liquid can be used with several types of mechanical devices to give indications of liquid level. The indicator can be made recording, and can be constructed to transmit readings to a remote location. The *float indicator* can also be used to indicate, by proper adjustment of float density, the level of the interface between two liquids insoluble in one another.

Where the float indicator may move too far for convenience, a *buoyancy indicator*, loaded by a spring to keep it from rising too far, may be employed. The move-

ment in this case is not identical with the liquid level but is proportional to it. A special type of buoyancy meter may also be used to indicate interface levels between two liquids.

A rather ingenious device is sometimes used for measuring liquid levels in tanks which are under considerable pressure. A small auxiliary tank may be connected to the main tank by flexible tubing connections. The small tank becomes a gage tank in which the liquid level in the main tank is determined by its weight.

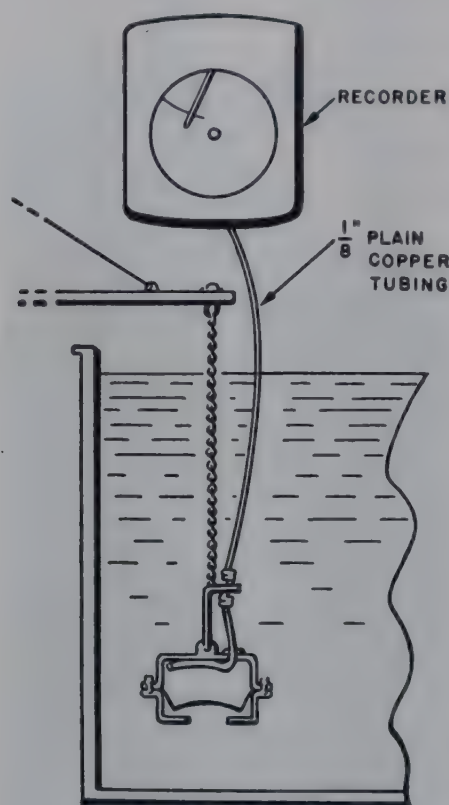


(Penberthy Injector Co.)

Figure 59. Sight Glass
(Armored pattern).

Inferential Liquid-level Indicators

Pressure-activated Indicators. Most of the inferential liquid-level indicators measure liquid level by determining the weight of a column of the liquid, the weight being converted by appropriate means to hydrostatic head to give the actual level measurement. A simple means of reading liquid level in an open tank is



(The Foxboro Co.)

Figure 60. Liquid Level Indicator; pressure diaphragm type.

to connect a pressure gage to an opening near the bottom of the tank. Through a knowledge of liquid density, hydrostatic head can be immediately converted to height of liquid above the fitting.

A widely used method for measuring hydrostatic head is to measure the pressure required to force air down a pipe immersed in the liquid. This is especially adaptable to open tanks, but the quantity of air can be small and it can therefore be used in closed tanks. The *bubbler gage* has several advantages; the pressure gage can be located at some distance from the tank, and the gage lines are kept relatively free of the liquid being gaged.

Liquid-level gages in which hydrostatic pressure at the bottom of a tank is transmitted by the movement of a diaphragm or a bellows immersed

in the liquid are often used if the nature of the liquid permits the introduction of such a device under the surface.

Temperature-activated Liquid-level Meters. A liquid-level device sometimes used on steam boilers measures the level by means of the expansion of a metal tube; the greater the length of tube exposed to the steam the greater is the expansion of the tube. Since this device exerts positive pressure it is often used as a control unit as well as an indicator.

Electrical Liquid-level Meters. Various electrical and electronic

devices have been developed for measuring liquid level. Most of these, however, measure or indicate levels when a certain predetermined point has been reached; the electrical impulses generated are frequently used for control purposes or as a means of activating an alarm.

Continuous Volume Measurement of Liquids. There are a large number of different meters available for the continuous measurement of liquid volume. The first choice between meters probably would be based on the desirability of reading instantaneous velocities as well as total flow, and upon operating conditions, such as the type of conduit in which the liquid is flowing, the viscosity of the liquid, its actual velocity, its temperature and the allowable pressure drop through the meter.

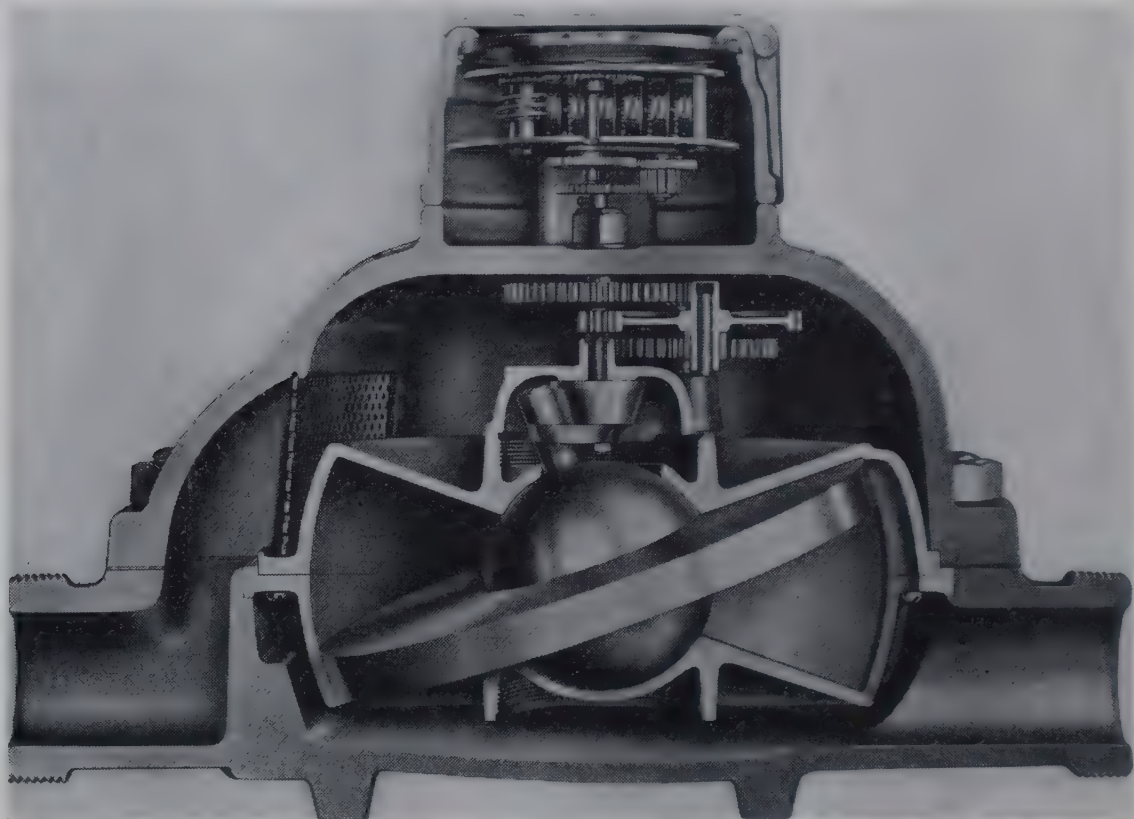
Continuous meters for liquid flow fall into three general types: (1) Positive-displacement meters, which measure the actual volume of liquid passing through the meter; (2) Inferential meters, which indicate flow by measuring some element or factor related to flow rate. This factor is usually the velocity which in turn may be measured by still other elements related to velocity. (3) Material or heat addition meters, which add either material or heat to the stream and calculate stream flow by the downstream concentration or temperature.

Volumetric (Positive) Meters

In this class of meters the actual volume of liquid is measured by repeatedly filling and emptying compartments of known volume. Total flow can be calculated by simple counters. For the most part, however, these meters are not satisfactory for observation of instantaneous rates of flow and can, at best, give only average flow rates over some interval of time. Many of these meters are externally driven and are, therefore, pumps as well as meters. Other meters derive the motive power for activating the meter from the pressure drop of the liquid flowing through them.

Of the positive displacement meters which are activated by the force of the liquid passing through them, the *nutating disk* is by far the most important. Virtually all domestic water meters are of this type. Since they are in such large scale production, they

are cheaper to buy than their rather intricate design would indicate. In those cases where the liquid is reasonably fluid, contains no solids, and is noncorrosive toward the metallic elements of the meter, the nutating disk meter is a very satisfactory device.



(The Buffalo Meter Co.)

Figure 61. Liquid Meter; Nutating disk type (Sectionalized view).

The nutating disk meter consists of a light-weight disk which is caused to nutate on its axis and alternately open compartments, first to the inlet port and then to the exit. The disk literally floats in the liquid passing through the meter. Errors of over 1 per cent are rare. Pressure drop through the meter is fairly high, and volume rates of more than 350 gallons per minute are seldom handled.

Several other types of positive-displacement meters have been developed which have found fairly wide use. Most of these are somewhat similar to ordinary rotary or piston pumps but have devices to reduce friction and minimize the serious pressure drop through them.

Virtually any type of positive-displacement pump, such as the

ordinary piston, rotating piston, screw, gear, or vane pump may be used as a meter. They are often used to serve the dual purposes of metering and pumping.

Inferential Meters

The most important meters for industrial use are those which measure some element of the flow of fluids such as the velocity, pressure drop when passing an obstruction, or some other property which can be related to total flow by well-known hydraulic formulas.

Velocity Meters. The velocity meter is the most nearly direct-reading of all the inferential meters. This instrument is used to indicate flow velocity past the meter. By calculating the average cross-section of the flowing stream and multiplying this by the liquid velocity, flow rates can be readily ascertained. In contrast to many other types of meters, several types of velocity meters are suitable for use in open channels.

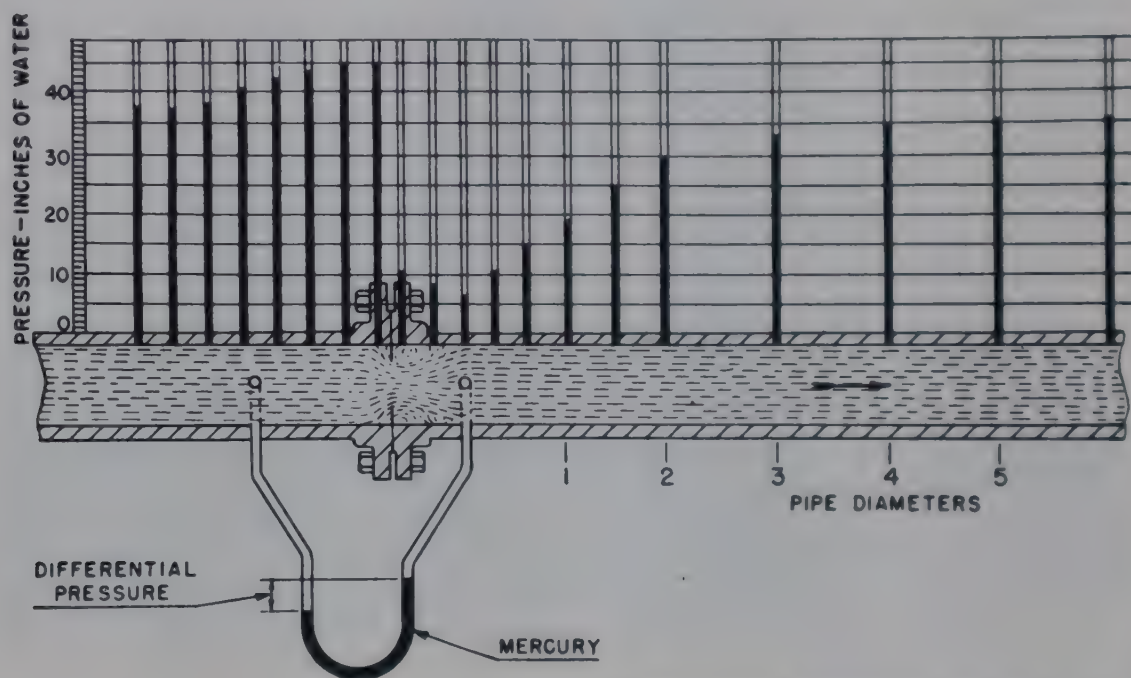
All velocity meters take the general form of a propeller, screw, helix, or turbine which is turned by the movement of the fluid through the meter. Frictionless bearings in which the propeller is mounted offer a very small frictional drag to the rotating element. The propeller, screw, or helix is normally mounted axially in the flowing stream. Blades are rarely more than 0.8 of the diameter of the pipe.

Velocity meters have the advantages of much greater capacity and lower cost compared with the positive-displacement type of meter. There is a much smaller pressure drop, and liquids containing appreciable quantities of solids can be measured without harm to the meter. Accuracy of this meter is somewhat variable, depending on velocity distribution and frictional drag. It is not as suitable as the volumetric types for either very low flow rates, or for highly viscous materials.

Differential Pressure Meters. Probably the most important single principle employed in the design of flow meters is that if a liquid, flowing in a pipe, is led through a constriction in the pipe, the velocity is quickly increased and an abrupt reduction in pressure occurs. This pressure reduction is directly related to the rate of flow of the liquid through the constriction. Pressure

recovery occurs as the liquid decreases in velocity downstream from the constriction.

The simplest and most easily installed device for providing a constriction is the *orifice plate*, in which a hole (orifice), somewhat smaller than the pipe diameter, is drilled. This plate is usually installed between the two faces of a flange coupling, and it, together with two pressure taps placed at the correct points in the pipe, completes the installation of the portion of the meter installed in the pipe.



(Minneapolis Honeywell Regulator Co.)

Figure 62. Pressure Differential Developed by Orifice.

The orifice opening is usually circular, with carefully cut, smooth edges and is centered in the pipe. It may, however, be eccentric or segmental if it is to be used for metering liquids carrying an appreciable quantity of solids.

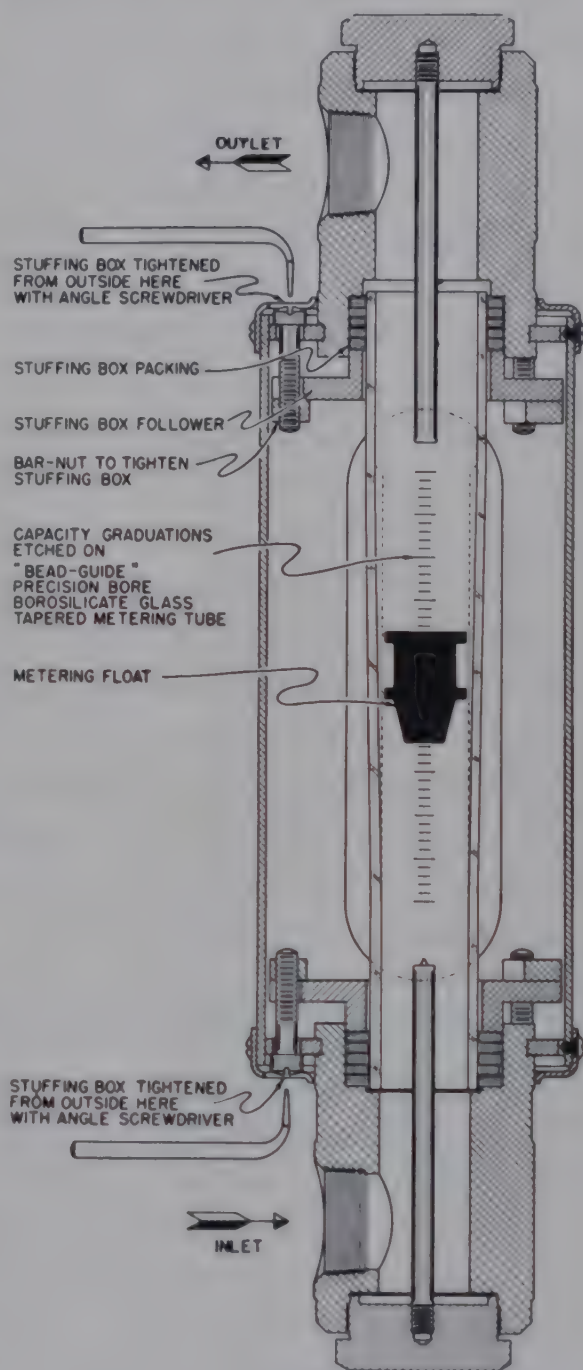
For high velocities an ordinary orifice plate may give poor accuracy, the permanent pressure drop may be large, and wear by erosion may be excessive. To overcome these difficulties, the flow nozzle, venturi tube, or venturi nozzle may be substituted for the orifice plate. These devices, at materially higher initial cost, overcome most of the deficiencies of the orifice plate.

The pressure differential set up in the pressure taps is ordinarily read by means of a liquid-in-glass manometer. To be

made indicating by means of a pointer on a scale, or to be made recording, a float may be placed in one leg of the manometer and connected to the indicating or recording device. The readings in an ordinary manometer are non-linear with flow rate. There are, however, specially shaped manometers which give linear readings.

Area Meters. Another general type of inferential meter is one in which the rate of flow is computed from the area change of a constriction or obstruction in the line, across which the pressure differential is maintained constant. Area meters are of three general patterns; the movable bob or plug which develops the area completely around the obstruction, the piston type which exposes an orifice area in the side of the cylinder as the piston is lifted, and the gate type in which an orifice opening is manually or automatically regulated based on pressure differential.

The *rotameters*, the best known of the area meters, have the general advantages of being reasonably accurate, corrosion resistant, having uniform graduations and wide ranges, and being small in size and self-contained. The meters are, on the other hand, fragile, difficult to use with opaque fluids, rather expensive, especially in the larger sizes, and are not easily converted into a totalizing meter.



(Fischer and Porter Co.)

Figure 63. Variable Area Meter.
Rotameter type.

Head Area Meters. A meter in which both the head and the area are varied, one as a function of the other, is available for the measurement of flow rates in open channels. This meter comes in two general styles, the weir and the hydraulic flume.

The *weir* consists of a dam having a rectangular- or wedge-shaped opening through which the liquid is caused to pass. A slight head is developed as the liquid level ahead of the dam rises slightly above the bottom of the opening in the weir. Measurement of this head is made by means of a float, a hook gage, or a still well. The head which is produced is related to the flow rate.

If little head is available, or if the liquid carries some silt, a flume in which the side walls have a venturi-like shape is sometimes used. The characteristics of flow through this flume are not greatly different, although much smaller in proportion, than in the closed venturi meter.

Force Meter. Meters have been developed which give a rough indication of fluid velocity by the impact of the moving fluid upon an element free to swing in the stream. The angular deflection of such an element is related to the fluid velocity. Two types, the hydrometric pendulum for open channels, and the swinging vane, or sight flow indicator for closed channels, are available.

Material or Heat Addition Meters

Dilution Meters. Metering of material in a large stream is possible by the addition of a second material whose concentration at high dilutions can be readily and accurately determined. If this second material is carefully metered as it is added, a very simple calculation will give flow rates. Material such as dyes, the concentration of which can be determined by color, acid or alkaline materials which can be titrated, or salts which can be analyzed by electrical conductivity, are used in this technique.

While these techniques are not usually to be recommended for ordinary metering service, they are, nevertheless, extremely useful in those situations where more conventional metering devices cannot be installed or used, or where metering is required only occasionally.

Thermal Meters. If, in place of material being added to a

liquid stream, a known quantity of heat is introduced, the increase in temperature becomes a measure of the quantity of liquid passing the heating element. While this method is widely used in gas measurement its use in liquid metering is limited by the relatively high heat capacity of liquids.

PROPORTIONING OF LIQUIDS

The controlled addition of the liquids to a stream, a process, or any apparatus is always achieved by the use of a valve. Many valves are available which give reasonably satisfactory service as throttling valves. It is in the various methods of activating the valves that the ingenuity of the instrument maker is displayed.

Proportioning Liquids by Weight

Except for one or two notable exceptions, it is rare that liquids are handled on a direct-weight basis. Nearly all automatic machines designed for filling cans or bottles with fluid of any kind are designed to fill on a weight basis. The container receiving the fluid is placed on a weighing platform which trips and closes the filling valve when the proper weight has been introduced. It is customary to weigh liquid out of a tank in which it may have been measured by weight.

There is no operation involving the continuous addition of liquids by weight comparable to the several methods of proportioning solids by weight. It is too simple to control liquid flow by volume and too easy to convert volume to weight for any effort to be spent in devising methods for continuous weighing of liquids as they are added to a reaction mass.

Proportioning Liquids by Volume

There are many operations in chemical manufacturing in which liquids are fed batchwise to a reaction mass. For batch feeding, liquids are measured out of the storage tank by noting changes in level, or are measured into the receiving unit in a similar way. Intermediate measuring tanks may also be used.

The continuous control of the flow of liquids is accomplished entirely by valves, with several standard patterns, notably the plug valve and the needle valve, being favored. Manual control

in which valve openings are adjusted by hand to regulate flow to a predetermined rate is common.

Automatic control mechanisms are presently available which will not only maintain flow rates at preset levels but will change them over a predetermined schedule.

The control of liquid movement is also effected with accuracy by use of one of the several positive displacement pumps. They are to be recommended in any case where precise control is a prime requisite.

QUANTITY MEASUREMENT OF GASES

Nearly all the methods in use for metering liquids, with some small modification, are equally useful for metering gases. A few techniques in wide use are applicable to gases only.

Like liquids, gases are almost always measured by volume. The measurements can be made with accuracy, either batchwise or continuously.

Batch Volume Measurement of Gases

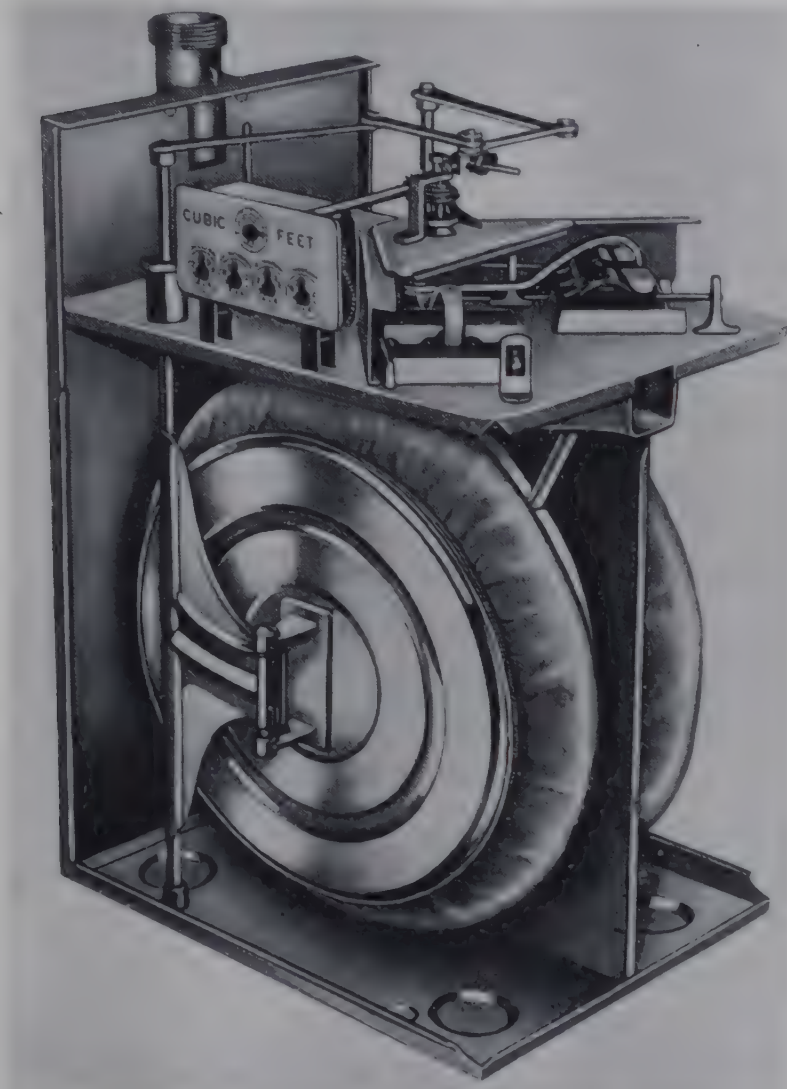
Gases are frequently measured in batches in tanks. This can be accomplished either in a variable volume tank, or in one having constant volume with pressure differences indicating changes in volume of the gas.

The ordinary lift type of gas holder, either water-sealed or waterless, can be easily made indicating as to height, and hence as to volume. This type of measuring device is quite accurate. Any tank which can be filled with a liquid, and which is provided with a level indicating device can be used as a gas-measuring tank. The space above the liquid becomes a variable-sized gas holder.

A fixed-volume tank can also be used as a gas-measuring device if it is provided with accurate temperature and pressure gages. This tank provides some advantages over the water-filled type in that it can meter gases which would react with water. However, the accuracy of a fixed-volume dry tank leaves much to be desired, and it cannot, of course, be completely emptied of the gas being measured without some loss of the gas.

Continuous Volume Measurement of Gases

Almost any of the techniques used for the continuous measurement of liquids are applicable, sometimes with slight modifications, to the measurement of gas volumes. In addition, there are



(American Meter Co.)

Figure 64. Bellows Gas Meter.

several types of metering devices which are particularly well adapted to gas measurement.

Positive Meters. There are three types of positive meters of special interest in the continuous measurement of gases. These are the bellows meters, the lobed-impeller meters, and the liquid-sealed drum meters. The bellows meter has no exact counterpart in liquid measurement but resembles the nutating disk in general principle; the lobed impeller is a specialized design of gear pump;

and the liquid-sealed drum is the gas version of the rotating-bucket liquid meter.

Inferential Meters. Velocity Meters. The velocity of a moving gas stream can be gaged by using a *rotating vane anemometer*. These devices come in two general styles, one of which has to be faced more or less into the moving gas stream and the other being activated by gas moving in any horizontal direction. The first type consists of a set of rotating vanes, somewhat similar to electric fan blades, attached to a shaft which is mounted in nearly frictionless jeweled bearings. A counting mechanism records the number of revolutions of the propeller. The second type of velocity-measuring anemometer is the familiar weather station wind velocity meter. This instrument has hemispherical cups mounted at the end of spokes radiating horizontally from a central vertical shaft. These vanes are activated regardless of the wind direction and will drive the shaft at a speed proportional to its velocity. These anemometers are not as accurate as the propeller type, but their ability to accommodate themselves instantly to any direction of air movement is of importance.

Differential Pressure Meters. Orifice meters and the various types of venturi meters are constructed, installed, and used in the measurement of gas velocity in the same manner as they are for liquids. There is one differential-pressure instrument which is used almost exclusively for measuring gas velocities. This is the *Pitot tube*, which measures the difference between the static pressure and the velocity or impact pressure at any point in a conduit carrying a moving fluid. Pitot tubes are often used for portable and exploratory work because of their small size and simple construction. However, because they produce low pressure differentials, and because they are difficult to calibrate and keep in proper operating condition, they are rarely used in permanent industrial installations.

Area Meters. All forms of the rotameter and other types of area meters used for liquid flow measurements are made in almost identical patterns for the metering of gases. These instruments offer the same advantages when used for gas as for liquid measurement.

Force Meters. A force meter, similar in general design to the liquid force meter, is the *deflecting vane anemometer*. In this instrument a vane, pivoted on a jeweled bearing and delicately balanced by means of a spring, is caused to deflect by the force of the gas blowing against one face. Since the deflection is independent of the size of the duct, a small jet can be led out of the main duct and can be used to give readings on the meter located completely outside the main stream of gas.

Material or Heat Addition Meters. *Dilution Meters.* The addition of carbon dioxide, water vapor, or other gases in metered quantities to a flowing gas stream, followed by a rapid analysis of the gas to determine concentration of the added material is just as feasible for gases as it is for liquids. The content of both carbon dioxide and water vapor can be quickly and accurately determined when present in a gas. An easy calculation will give rate of gas flow.

Thermal Meters. Thermal meters for gas measurement are more important than they are for liquid metering. At least two types of thermal meters are in common use. One of these, the Thomas calorimetric meter, determines the effect of adding a known quantity of heat to the gaseous system. The other, the hot-wire anemometer, determines the effect of a stream of gas on a hot body. The *Thomas calorimetric meter* consists essentially of an electric heating element to which the power input can be accurately measured, and two highly sensitive and accurate thermometers for measuring the difference in temperature before and after the addition of the heat. Actually two techniques are possible. One is to maintain constant heat input and note temperature differences; the other is to maintain a constant temperature difference and measure the heat input.

The *hot-wire anemometer* consists of a small resistance wire inserted in the gas stream. The wire has a known electrical resistance and is maintained at a definite temperature by maintaining a known electrical input. As the gas flow varies, the current is adjusted to maintain the resistance, and hence the temperature, constant. The current reading is converted to velocity.

PROPORTIONING GASES

Gas flow control is effected by the same means, and is subject to the same operating difficulties as those described for liquid flow control. The use of valves is always indicated, and whether the valves are to be controlled automatically or manually depends upon the type of flow measuring instrument in use and the operation requiring the proportioning of gas.

11 : THE MEASUREMENT AND CONTROL OF PRESSURE AND TEMPERATURE

Measurement of Pressure

Pressure measuring instruments

Balancing gages

Elastic deformation gages

Miscellaneous gages

Protective devices for pressure measuring instruments

Pressure Control

Measurement of Temperature

Temperature-measuring instruments

Expansion-type instruments

Melting point of a solid (pyrometric cones)

Electrical resistance thermometers

Electrical potential instruments

Radiation pyrometry

Control of Temperature

Nearly all chemical reactions proceed most effectively at some definite temperature and pressure to produce the maximum yield and quality of product, and to give rapid reaction rates with minimum production of by-products through side reactions. It is essential, therefore, that any planning for operations involving chemical reactions include full consideration of temperatures and pressures and the techniques involved in their measurement and control. Temperature and pressure control may also be required for regulating the viscosity of a liquid, keeping a solid above its melting point, a gas below its critical pressure and temperature, the prevention of loss through volatilization, or achieving many other purely physical objectives.

Pressure and temperature regulation may mean their controlled reduction as well as their increase.

MEASUREMENT OF PRESSURE

Pressure measurement is perhaps the most fundamental of all industrial measurements. Some of the methods for measuring almost every variable, such as temperature, gas or liquid flow rates, liquid levels, and others, are dependent on pressure-measuring techniques.

Instruments for pressure measurement are available for a wide range of pressures and vary in complexity of design, cost, and ease of installation. The selection of a pressure-measuring technique and instrument is dependent on a considerable number of factors. Some of the more important of these are:

1. Pressure to be measured
2. Difficulty of observation
3. Desirability of recording or of instrument control
4. Degree of accuracy required
5. Cost
6. Ruggedness
7. Ease of installation
8. Ease of maintenance.

Pressure-measuring Instruments

Most pressure-measuring instruments fall into one of two general classes (1) those in which a pressure is measured by balancing it against a force of known intensity, and (2) those in which the pressure is measured by the elastic deformation of a metallic spiral, diaphragm, or bellows. Pressure-measuring instruments of all types usually measure the pressure differential between a known pressure (such as that of the atmosphere) and the pressure to be measured. Only in very few cases do instruments directly measure absolute pressure.

Balancing-type Pressure Gages. *Manometer.* The manometer, a pressure-measuring instrument which balances a column of liquid of known density against the unknown pressure, is in its simplest form a U-shaped tube containing the liquid of known density. As manometers are often liquid-in-glass, they are not recording or controlling, and are limited to reasonably low pressures. However, the liquid can be enclosed in metallic tubes and the levels indicated by floats or electrical contacts. This

type can easily be made recording or controlling. Manometers using metal tubes can be used in systems carrying pressures up to 2,000 psi. The maximum pressure difference which can be readily determined, however, is in the range of 10 to 20 psi.

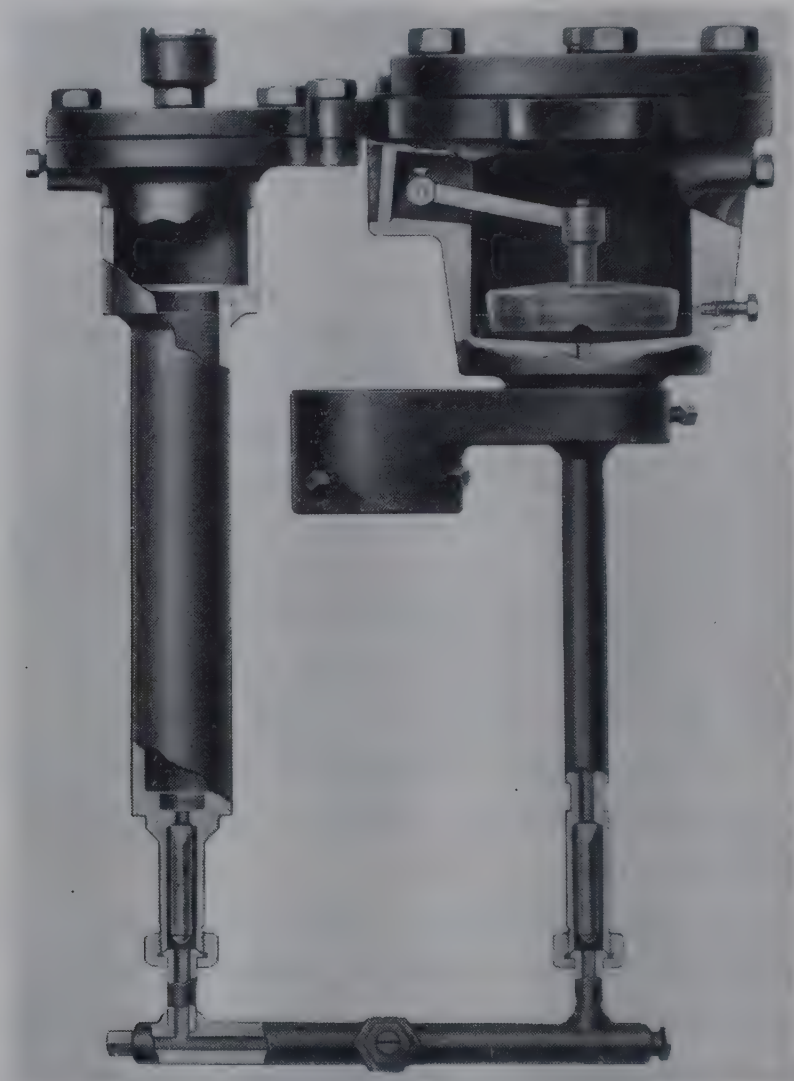
The manometer is made in a number of styles to give special operating advantages. The simple U-type manometer is improved somewhat by placing two straight legs into a sealed basin. In this manner tubes can be replaced easily if they are broken or fouled. Other improvements are metallic headers, by-pass valves, and metallic frames. One of the difficulties of the U-type manometer is that the graduated scale must be lowered or raised to the zero point, or the reading must be taken as two readings, one upward and the other downward from the zero point, and the pressure determined as the sum of these two readings. This is always inconvenient and often confusing. For this reason, the *well-type manometer* has been devised, wherein one leg is a basin of sufficient capacity to maintain virtually constant liquid level in itself, with considerable variation in the upright leg. One drawback of the ordinary vertical U-tube manometer is the small readings obtained when slight pressure differences are to be measured. The *inclined-tube manometer* can be used to magnify the readings by as much as 5 to 10 times, depending on the angle of inclination of the tube.

The *two-liquid gage* is another instrument for increasing the reading above that which can be obtained by the ordinary U-tube gage. Each is filled with a different liquid. The liquids should be of a similar, but not the same, specific gravity, and they must be immiscible. This manometer is made with a large reservoir at the top of each tube, the U-tube joining the two reservoirs being of small diameter. The liquids are filled to rise well into the reservoirs and the level is read at the interface between the liquids.

The *formed well manometer* is a special design to give linear readings with the pressure differentials developed by orifice type flow meters.

Bell-type Gage. The bell-type gage is similar in principle to the water-sealed gas holder. It utilizes the lifting force of a liquid-sealed bell chamber to provide the mechanical movement

of the indicating or control mechanism. The instrument is sensitive to very small pressure differences and yet is quite rugged. There are several styles of bell-type pressure gage. The *balanced-lever bell gage* consists of a bell suspended from one side of a



(Taylor Instrument Co.)

Figure 65. Manometer; Float type (Sectionalized view).

lever arm with a balancing weight suspended from the opposite end of the arm. Any difference in pressure between the outside and inside of the bell will cause movement of the weighted beam. The *floating-bell gage* is similar to the balanced-lever gage except that the bell is floated on mercury rather than being suspended by a balance arm. The indicating or recording mechanism is connected directly to the bell by means of a yoke. If, in place of the lever arm, the bell is supported by a spring, the *spring-*

balanced bell gage is obtained. Since any change in the resiliency of the spring will cause serious errors in the readings, this instrument is not inherently as accurate as one of the first two types.

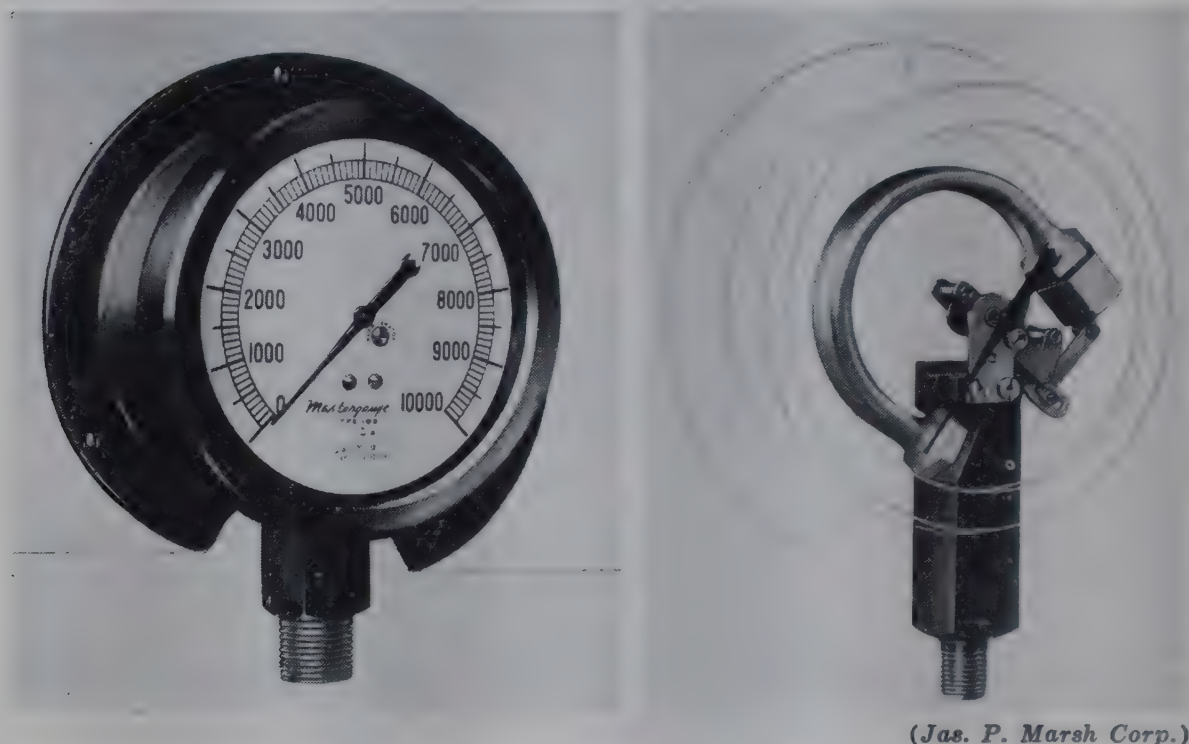
The *Dubrovin vacuum gage* is similar in appearance but different in principle from the other bell-type gages. This gage consists of a glass bell immersed in mercury. The space outside the tube is evacuated, and as this is done the mercury tends to be pulled out of the bell. The bell rises to accommodate the smaller load within it.

While no different in principle from the ordinary straight-side bells, the *formed bell*, having a greater displacement as the bell sinks in the sealing liquid, or one having a variable weight as it is raised or lowered, is used with many liquid flow-measuring instruments in order to convert nonuniform pressure readings into uniform intervals of fluid flow.

The Limp-diaphragm Gage. The limp-diaphragm gage has been developed to meet the need for a gage which will not require the servicing of one of the liquid-sealed types, and yet which will give good accuracy at low pressures. The diaphragm of this gage is made of oil-treated flexible leather which, being completely slack, offers no resistance to motion. The linkage assembly for recording the movement is attached to a plate held in the leather diaphragm. A spring also attached to the plate provides a loading force to counteract the pressure. A casing to prevent blow-out of the diaphragm and the indicating device complete the assembly.

Piston-type Gage. The pressure gages previously described have been designed for pressures in the low ranges (up to about 20 psi). The piston-type gages meets the requirements for a balancing gage which will handle pressures as high as 5,000 psi. This gage is simply a small piston operating in a pressure-sealed cylinder, the pressure on the interior of the cylinder being balance by weights (*dead weight gage tester*), a coil spring (*spring-opposed piston gage*), or by means of a mercury cup and float adjusted in weight by a secondary hydraulic lift (*Bailey power-type pressure gage*). The piston gage can be made to give very precise measurements.

Elastic Deformation Gages. Nearly all the balancing gages require constant attention and maintenance to give satisfactory results. The need for a gage which can be produced at low cost, and which is simple, compact, and rugged, has led to the development of a number of gages in which the deformation of an elastic membrane is used as the activating device for indicating pressure.



(Jas. P. Marsh Corp.)

Figure 66. Pressure Gage; Bourdon tube type.

These gages, made in both high and low pressure ranges, are all indicating, transmitting their pressure readings to a dial or scale. They can also readily be made to activate a recording pen or trip a control device.

The *Bourdon tube gage* is the standard of the pressure measuring instrument field. It is mass-produced and hence is cheap. It is easily installed and where properly used gives reasonable accuracy. It consists of a thin-walled metal tube, flattened on diametrically opposite sides to produce an elliptical cross-section, and bent lengthwise into the form of the segment of a circle. The tube is attached rigidly to a pressure inlet at one end. The other end is sealed and is free to move. The free end is attached to a linkage which moves a pointer. As pressure is applied, the tube attempts to regain its circular cross-section and

in so doing tends to straighten out. The resultant motion of the free end is transmitted through the linkage which moves the indicator. Spiral and helical pressure elements have been made to give greater magnification of movement, and hence somewhat improved sensitivity over that obtained by the standard Bourdon tube.

The Bourdon tube gage in all its styles and capabilities is a widely used instrument, and is usually the one first considered in viewing the possibilities of techniques for pressure measurement. It is not, however, usually as sensitive nor as accurate in low pressure ranges as are the balancing types of gage. Its low cost and great ruggedness make it a favorite instrument in the pressure ranges in which it will operate satisfactorily.

The Metallic Diaphragm Gage. A metallic diaphragm mounted in a rigid support will be deflected by a pressure, the deflection being

Figure 67. Pressure Elements. Top—Helical element. Middle—Spiral element. Bottom—Interim diaphragm element.



(The Foxboro Co.)

roughly proportional to the difference in pressure applied to the two sides. A linkage attached to the center of the diaphragm transmits the movement to an indicator. Corrugations in the surface of the diaphragm will increase the movement of the indicator linkage by as much as four times. This gage has many faults and hence is little used as an industrial instrument. It does have some use for low pressure measurements.

The Metallic Bellows Gage. This gage was developed to meet the need for a gage of the elastic deformation type which would be more sensitive to low pressures than the Bourdon tube gage, would have fewer troublesome features than the diaphragm gage, and yet be capable of developing sufficient direct power for actuating recording or control mechanisms. The bellows element is simply a specially corrugated (banded) tube closed at both ends. One end is fixed to a stationary plate, and any change in the relative pressure inside and outside the bellows will cause a movement of the free end of the bellows.

Miscellaneous Gages. There are several other types of pressure gages which, though not widely used, are still of sufficient interest and novel enough in principle to deserve mention.

The carbon-resistance gage measures the change in resistance of a pile of carbon plates when pressure is applied. The resistors are composed of several plates of carbon held between copper disks. Gages of this kind are made in several types to measure various pressure ranges from 1 ounce to 40,000 psi. The *piezo-electric gage* consists of a stack of alternate quartz and thin metal plates. The charge which is developed in the quartz by the application of pressure is a function of the pressure applied.

Manganin Wire Resistance Gages. Pressures above 15,000 psi or high vacuums can be measured by the resistance change of a small diameter section of manganin (copper-manganese-nickel alloy) wire. The design of the hot-wire gage depends on the fact that the thermal conductivity of a gas varies with the pressure. The thermal conductivity is, in turn, measured by the amount of electricity required to maintain the temperature of a resistor at a constant level, or by measuring the change in temperature of the wire when being supplied with a constant input of electric power.

The hot-wire gage is most used in measuring pressures in the high vacuum range.

The ionization gage, a laboratory instrument, measures pressures down to $1/10$ micron by measuring the ionization of a gas by a definite electron current.

Many industrial uses are currently being made of very high vacuums. There is a distinct need for a gage of a semi-mechanical character capable of accurately measuring absolute pressures in the ranges from $1/100$ micron to one or two millimeters of mercury. The *McLeod gage* is the best instrument so far available to meet this need. This gage has a movable mercury reservoir which permits trapping a small volume of gas from the system in a capillary tube. When the reservoir bulb is moved back to the measuring position this gas is compressed to a smaller volume at a higher pressure, which can be measured by the difference in the height of two mercury columns.

Protective Devices for Pressure Gages

Many pressure gages are used in service where they may be subject to damage. Protective devices to prolong the life of these instruments and to assure their proper performance should always be used, and these should be inspected regularly to see that they are functioning properly.

Devices for Protection against Pulsation. Pulsating pressure is one of the most serious causes of instrument damage. The simplest method of protection is to install a valve between the gage and the pressure system, and to close the opening in the valve to a point where movement through it is sluggish. Such small openings are difficult to maintain, however, and there is always a risk that the opening will be clogged by solid particles.

More practical and positive means of pulsation damping are available in several devices made especially for the purpose. One device smooths out the pulsation by a maze of small passages through which the pressure is transmitted to the gage. Another method uses a tube containing a felt plug and filled with glycerin which, in working its way back and forth through the plug, levels out pulsations. A third device consists of a piston heavy

enough to possess considerable inertia. Another device consists of a tube divided into a series of compartments separated by metal disks. A small hole is drilled at the center of each disk, and a wire somewhat smaller than the hole passes longitudinally through the unit.

Protection against Corrosion. Many gages have very thin-walled metal pressure-sensitive elements. These can be quickly damaged or destroyed by exposure to corrosive gases, vapors, or liquids. Protection can be afforded by means of a liquid seal, or better by sealing with a corrosion-resistant flexible diaphragm. In the second case, the system between the diaphragm and the gage must be kept filled with glycerin or some other hydraulic liquid.

Protection against Mechanical Damage. Mechanical damage may result from vibration or from accidental misuse. Mechanical damage resulting from overload can be prevented by blowout disks, or can be reduced materially by using a gage having a pressure range extending well above the maximum pressure which is anticipated.

Protection against Heat. The pressure-sensitive elements of the Bourdon or bellows gages should be protected from live steam. A siphon trap in which condensate can collect is usually quite adequate for this purpose.

PRESSURE CONTROL

The control of pressure within a system usually means the control of flow of gas or liquid into or away from the system. It is seldom necessary to regulate pressure by regulating temperature. Consequently the problems of pressure control are almost identical with those of the control of material flow. The control of pressure can be effected by several types of so-called pressure-regulating valves, which have been described in the second chapter. If a system is under a vacuum the control of pressure normally signifies the necessity for producing a vacuum. Pumps for this purpose have also been described.

MEASUREMENT OF TEMPERATURE

Temperature, the indication of the quantity or level of heat in a mass, is one of the most important factors relating to the con-

duct of chemical reactions; its accurate measurement and control are of the utmost importance.

The selection of an appropriate technique for temperature measurement may often depend as much upon the immediate availability of an instrument as any other factor. However, barring this forced choice, there are several points which must be given consideration in the selection of the proper technique for temperature measurement. Some of these are:

1. The temperature range to be measured
2. Whether indicating, controlling, or recording is required
3. The accuracy and sensitivity required
4. Costs, both first cost and installation
5. Probable life, resistance to damage
6. Ease of observation
7. Portability, adaptability, and size
8. Ease of maintenance
9. Constancy of calibration (accuracy over a period of time).

Temperature-measuring Instruments

Temperatures can be measured by more fundamentally different techniques than any other variable. Moreover, all of these techniques have some rather important industrial uses. The instruments available for measuring temperature can be classified, roughly at least, into several general classes, depending upon the principles of operation, as follows:

- a. Expansion of a solid, liquid, or gas, and vapor pressure of a liquid
- b. Melting point of a solid
- c. Electrical resistance
- d. Electrical potential
- e. Radiation intensity

Expansion-type Instruments. All materials expand when they are heated. Provided with a means for its reasonably accurate measurement, the increase in volume of a substance can be made a measure of the increase in temperature.

Liquid Expansion Instruments

The expansion of a liquid can be measured rapidly and easily. From this fact there has been developed the most widely used of

all thermometers—the liquid expansion type. They are made literally by the million. They are very low priced, notwithstanding their intricacy of design and their accuracy of construction and calibration.

Changes of temperature may be read as the movement of visible columns of liquid in the stem of the liquid-in-glass thermometer, or may be evaluated by pressure measurements made in a Bourdon tube, bellows, or diaphragm type of pressure gage. Both types of liquid expansion thermometers are in wide use. The pressure-actuated instrument may be cheaply made, but it is usually somewhat more expensive than the liquid-in-glass thermometer. It is not quite as accurate as the liquid-in-glass thermometer but it has several advantages: (1) more rugged construction, (2) easy readability, (3) placement of the dial at some distance from the point at which the temperature is actually determined, and (4) the possibility of being made recording or controlling as well as indicating.

The liquid-in-glass thermometer is made in two general styles: (1) the laboratory all-glass thermometer, available in several different patterns, such as the standard type, the Beckmann, and maximum and minimum thermometers; (2) the industrial-type thermometer, in which most of the thermometer is firmly enclosed in a heavy metal casing to protect it from mechanical damage.

The chief variation of form of the industrial liquid-in-glass thermometer relates to the position of the bulb with respect to the stem of the thermometer, and to the several methods used for attaching it to the equipment on which it is to be used. The bulb can be in line with the stem (and scale) or can be made to project at 45° or 90° directly back of the scale, or 45° or 90° to either side. The bulb on some patterns is as much as 96 inches from the scale.

The ranges of the several thermometers are fixed by the liquid used and the glass in which it is contained. The working ranges of the various filling liquids are as follows: mercury, -30 to 925°F.; alcohol, -100 to 250°F.; toluene, -150 to 120°F.; pentane, -300 to 70°F.

Special glasses can be used at temperatures up to about

1,200°F. A special gallium-in-quartz thermometer will give readings up to about 1,800°F.

The pressure gage or dial-type thermometer is becoming increasingly important as a temperature-measuring instrument. Important for a long time as a relatively expensive but highly satisfactory instrument for recording or controlling temperatures, its use has been broadened considerably by the introduction of a thermometer of this type into the very low-cost field. This thermometer, which uses mercury, xylene, or alcohol as a fluid, simply holds the fluid in a metallic bulb and transmits the expansion of fluid, as the bulb is heated, to a standard pressure element such as the Bourdon tube or bellows. The instrument is rugged, fairly accurate, and more important, the bulb can be separated from the pressure gage by as much as 250 feet.

Gaseous Expansion Thermometers

Although the expansion of a gas is the basis of thermometry (the expansion of hydrogen near 0°C. is the foundation for the absolute temperature scale), gas expansion thermometers have little use outside the laboratory. They are suitable for precision measurements, but the bulb has to be quite large compared to the liquid-filled variety; they are not, therefore, practical for industrial use. Gas-filled bellows are often used in temperature-control work. This is the sensitive element in nearly all domestic heating controls.

Vapor-pressure Thermometers

A pressure-gage thermometer which uses the vapor pressure of a volatile liquid such as toluene, sulfur dioxide or ethyl chloride, is available. This arrangement produces higher pressures with an increase in temperature than does the gaseous expansion type, but in few cases is there a straight-line relationship between vapor pressure and temperature.

Solid Expansion Thermometers

Solid expansion thermometers are seldom used as industrial temperature measuring instruments, but are often used for controls. They are often called "bimetals." The phenomenon of

hysteresis—the lag which many metals exhibit in returning to their original condition after they have been heated—discourages their use where accurate measurement is required. However, since they are cheap, and deliver sufficient force to activate valves or open and close electrical contacts, they are almost universally used where rough control by a rugged instrument is required.

To give positive movement to the end of a small and compact element of sufficient magnitude that it can be measured, thin strips of two metals having different coefficients of thermal expansion are laminated firmly together. When these are heated there is considerable distortion (bowing) of the two strips. The simplest control uses two straight strips. In more complicated arrangements the metal strips are bent in the form of either a spiral or a helix.

Melting Point of a Solid. Another physical property which can be utilized for the measurement of temperature is the melting point of either a pure solid, or of a composition of known and reproducible melting point. The melting points of certain selected substances have become the standard check points for thermometer calibration. The melting point of pure water is the principal fixed point of thermometry. Other materials which can be prepared in pure enough state to give exact and completely reproducible melting points are also used.

There is only one industrial type of melting-point thermometer. This consists of a series of small ceramic “cones” (actually shaped like elongated tetrahedrons), which are compounded to have definite melting points. These “pyrometric cones” are placed in a hot zone, and the temperature noted is that which causes all the cones up to a certain number in the series to soften. Any series of cones is used but once and is then discarded.

Electrical Resistance Thermometers. Virtually all metals will change their electrical resistance with a change in temperature. Some, like platinum, copper, or nickel, have a quite high temperature coefficient of resistance. This property is utilized in the electrical resistance thermometer, a sensitive and accurate instrument which has had wide acceptance in industrial temperature measurement. The temperature-sensitive element consists of a carefully formed coil of fine wire supported on mica sheets,

or quartz or "plastic" rods, which are encased in metal or quartz protective tubes for shielding the wire against breakage and from contamination by the atmosphere in which they might be placed. Measurement of the change in electrical resistance with change of temperature normally is made with one of the several types of resistance-measuring instruments employing the Wheatstone bridge circuit. The range of these thermometers is from about -300 to $1,800^{\circ}\text{F}$. Platinum gives the greatest range; but nickel, because of its lower cost and excellent resistance-temperature gradient, is most used in the temperature range -150 to 300°F .

The advantages of the resistance thermometer include high sensitivity (temperature differences of 0.02°F . can be detected); ability to measure temperatures lower than can be easily or accurately measured by any expansion-type thermometer; the possibility of separating the temperature-sensitive element and indicator (up to $1/2$ mile); and the ease with which the temperatures can be recorded on a permanent record. Its major disadvantage is that for accurate measurement, a resistance-measuring instrument costing several hundred dollars must be used. Some of the newer "multi-point" recorders, however, can be used to take readings from as many as a hundred temperature elements, although they are ordinarily used for a much smaller number. Thus the cost of the instrument can be justified.

Electrical Potential Instruments. If two dissimilar wires are joined together and heated, an electromotive force is produced at the terminals of the wires leading from the heated junction. Knowledge of this phenomenon, known as the Seebeck effect, has led to the development of the class of instruments known as thermoelectric pyrometers or thermocouples.

The thermocouple consists of wires of dissimilar metals joined at one end and led away from the joint (couple) in insulated tubes to prevent further contact. A protective sheath to reduce mechanical and chemical damage to the couple completes the temperature-sensitive element. The e.m.f. produced may be measured by a millivoltmeter or potentiometer. Thermocouples of the various kinds of metals can be used for temperatures from -300 to about $3,100^{\circ}\text{F}$.

Thermocouples are low in first cost, are easy to repair and cheap to replace. Their accuracy is poor compared to the resistance thermometers, but compares favorably with that of expansion-type thermometers. The major expense of the instrument is the electrical measuring instrument, either a millivoltmeter or a potentiometer. Instruments which will simultaneously indicate and record impulses from several temperature elements are available.

Radiation Pyrometry. It is often necessary to determine temperatures at levels above those which any metal- or glass-enclosed thermometers or pyrometers will withstand, or at locations where it would be difficult or impossible to place contact thermometers. To meet these problems, the radiation pyrometers have been developed. These are based upon the principle that heat (radiation) is projected outward through space, independently of any motion of particles or molecules. Radiation in the visible range is ordinary light.

The radiation pyrometer is used for temperature measurement from 800 to 5,000°F. Some instruments have been made for measuring temperatures as low as 100°F. and for estimating temperatures well above the maximum limit of any temperature which can be determined by any other means. It is available in two general types: the optical pyrometer and the so-called "total radiation" pyrometer.

Optical Pyrometers. An optical pyrometer is simply a photometer in which the intensity of radiation from a constant standard source may be compared with the unknown intensity of the radiating body. In one type of this instrument a wedge of dark glass is slid across the optical field of view, gradually decreasing the observed intensity of the unknown source until it just vanishes. A scale which indicates the amount of movement of the wedge is calibrated to indicate temperatures.

Other types of optical pyrometer have means for making a comparison of the unknown intensity with one of known temperature. The most popular instrument of this kind is the disappearing-filament type. In this instrument an electrically heated filament, or its image, is superimposed upon the optical system through which the heated body is observed. The observed in-

tensity of the filament is altered in one instrument by changing the current input, in another by introducing a wedge of red-absorbing glass.

A polarizing type of instrument is available in which the light from the heated body and from a comparison lamp both pass through a spectroscope and polarizer. The light from these two sources is impressed upon a split field so that half the field is polarized at right angles to the other half. A nicol prism is rotated by the observer until both halves are of equal intensity. The angle of rotation is a measure of the temperature.

Another type of optical pyrometer can be made to record temperatures. Two photoelectric cells, connected in a bridge circuit, are arranged so that one receives light from the standard source, and the other from the unknown.

Several precautions must be observed in the use of the optical pyrometer. Reflection from a surface can introduce gross errors. Smoke or vapors surrounding heated objects will cause errors, as will any obstruction to light such as glass placed over the sighting hole.

Total Radiation Pyrometers. The total radiation pyrometer has been developed for use at lower ranges than the temperatures corresponding to the visible spectrum, to remove the necessity for visual comparison and the difficulty of duplicating results, and to record results more easily than can be done with the optical pyrometer. The total radiation pyrometer consists essentially of a series of lenses or mirrors or both, which collects radiation and focuses it on a temperature-sensitive element such as a bimetallic strip, resistance thermometer or thermocouple. An indicating system such as a pointer, or a millivoltmeter or potentiometer, and a diaphragm for cutting down the light intensity so as to vary the range, complete the instrument. Two general types of radiation pyrometers, classified according to the type of focusing arrangement (adjustable or fixed focus), are available.

CONTROL OF TEMPERATURE

Temperature control usually involves the flow of material (steam, fuel, air, heated gas), or electricity to a heated system. Consequently, any type of temperature-measuring instrument

which can be made to activate an electrical contact or to operate a valve can be used as a temperature controller. The only instruments which do not lend themselves to this use are the liquid-in-glass thermometers, pyrometric cones, and the visual comparison types of optical pyrometers.

The bimetallic thermometer is widely used as a temperature controller, the bimetallic strip being used as an actual contactor to open or close an electrical circuit which activates a mechanical device to control valves and material controllers. The direct contact points have been largely replaced in more modern instruments by the mercury-in-glass switch, which provides more sensitive control with a much smaller activating force, freedom from arcing and fouling of points, and generally improved operation. The bimetallic strip, and more recently, the gas-filled bellows, are used for self-operated control mechanisms.

The thermostatic steam trap is a typical case in which a bellows is heated directly to produce the movement to open or close a valve.

12 : MIXING OF MATERIALS

Mixing Techniques

Mixing materials with gases

Mixing materials with liquids

Mixing materials with solids

Intimate contact of reacting surfaces and the maintenance of uniform concentrations and temperatures in a reaction mass are vitally important in the conduct of any reaction. Mixing is, therefore, an operation of primary importance. It is also an adjunct to other operations having a wide range of objectives.

Mixing is often carried on simultaneously with other operations, notably with the reaction itself, and with grinding operations. In many cases the reaction is carried on in the mixer, where the mixer becomes in fact the reaction vessel; or the mixer may be an integral part of the reaction vessel. In the case of the grinder, the mixing operation often assumes a secondary role, at least as far as the design of the equipment and its operation are concerned.

A number of terms are associated with the mixing of materials. Agitation, for example, usually refers to the mixing of low-viscosity liquids by means of relatively high-speed devices. Kneading refers to the mixing of liquids or semi-solid masses of high viscosity. The mixing of one solid with another is often called blending. The same term is also frequently applied to the mixing of liquids or of gases. The preparation of stable emulsions is often called homogenizing.

Of the many factors affecting the choice of mixers, the following are most important:

1. Properties of materials

a. Physical state (before or during mixing operation)

aa. Solid

- aaa. Particle size
- bbb. Apparent densities (comparative)
- ccc. Moisture content
- ddd. Ease of wetting
- bb. Liquid
 - aaa. Viscosity
 - bbb. Comparative densities
- cc. Gas
- b. Effects of temperature (reactions which may proceed simultaneously)
- c. Corrosive properties
- d. Effects on exposure to air
- 2. Whether operation should, or must, be either continuous or intermittent
- 3. Limiting factors if mixer is to be used as reaction vessel, or if it is to be primarily a grinder
- 4. Quantities to be mixed
- 5. Relative proportions of materials
- 6. Order and rate of the addition of materials to the mixture
- 7. Degree of dispersion required
- 8. General practice in the particular industry involved
- 9. Availability and cost of equipment
- 10. Cost of power, operation, and maintenance
- 11. Ease of cleaning
- 12. Versatility.

MIXING TECHNIQUES

The designs of available mixers are legion. This is not unusual considering that uniquely different types of mixing equipment are required for each of the three different physical states and their combinations; that different types are required for handling material batchwise or continuously; and that further variations in type are required for mixing under different external conditions.

Mixing operations involving two states of matter should be classified according to the nature of the continuous phase or of the preponderant one, even if it is not continuous.

Mixing of Materials with Gases

It is frequently necessary to mix two gases, less often a requirement to disperse a liquid or solid in a gas.

Mixing a Gas with a Gas. Two gases, even those with as great a density difference as carbon dioxide and hydrogen, will slowly mix, even if the heavier carbon dioxide is carefully introduced in a lower layer. The natural diffusion of gaseous molecules and the convection currents which always seem to be present in gas masses will cause mixing, slowly perhaps, but certainly.

Normally there is little necessity for concern about the intimate mixing of two gases, even with the simplest of mixing devices. Sometimes when intimate mixing must be accomplished extremely rapidly—as, for example, in the mixing of air with gasoline vapor in the manifold of an automobile engine—considerable thought and experimental work preceded the production of a mixing chamber properly designed to give the degree of mixing required.

The techniques of gas mixing are simple. If one gas is already present in a container, the mere introduction of a second gas through an inlet pipe or nozzle will usually be adequate to produce a uniform mixture rapidly. Where the space in the tank may be too large to obtain a mixture promptly, an ordinary circulating fan, if mounted in the gas space, will give adequate and rapid mixing of a large volume. A centrifugal type fan, mounted either internally in the tank, or externally with ducts leading from the tank to the fan and back to the tank, will give very satisfactory mixing.

If two gases are brought together in a moving stream, complete blending is achieved almost instantaneously to provide a continuous mixing operation. The two gases, if at atmospheric pressure, may be introduced to the intake of a blower. Quantity regulation can be obtained by the use of throttling valves. When one gas is under pressure and the other is not, a gas jet or aspirator is a quite suitable mixer. If both gases are under pressure, mixing can be done in an empty chamber or a baffled column from which the mixed gases are conducted in a single stream, or can be

achieved in the open in the two wings of a jet, as for example, in the oxyacetylene torch or the laboratory blast lamp.

Mixing a Liquid with a Gas. It is sometimes necessary to mix a liquid with a gas, or more specifically, to disperse a liquid in a gas. The operation is essential in certain drying techniques and is occasionally carried out in connection with gas scrubbing. It is rarely carried out as a means for promoting a chemical reaction except in the case of the combustion of a liquid fuel.

Batch or continuous mixing of a liquid with a gas is usually accomplished by either pressure or mechanically operated atomizing nozzles. Occasionally liquids are dispersed into a gas by boiling the liquid and condensing the liquid as a mist in the gas.

Mixing a Solid with a Gas. Probably the largest single application of this mixing operation is the addition of pulverized solid fuel to an air stream for purposes of combustion. The burners used in this operation are, therefore, good examples of industrial units devised for the purpose of dispersing a finely-divided solid into a gas.

Finely-divided solids may be dispersed in a gas by simple mechanical entrainment if the gas is caused to travel at fairly high velocity. The removal of finely ground material from a pulverizer is an example of the application of this technique.

It is also possible to disperse solids by exploding or erupting them into the gas stream, or by heating an easily vaporized solid which is recondensed into a fine smoke as soon as it is cooled on contact with the atmosphere.

Mixing of Materials with Liquids

Mixing a Gas with a Liquid. It is frequently necessary to add a gas to a liquid as an accessory to a reaction or in conjunction with purification or separation steps; to produce a physical suspension of gas in the liquid (foam), which can be retained long enough for the liquid to be solidified around the gas bubbles; and to form semi-permanent dispersions of gases in high-viscosity liquids in order to produce some of the modern food preparations.

Since the techniques involved in this operation are markedly affected by the viscosity of the liquid medium, any consideration of the techniques of mixing must take this fact into account.

When the nature of a reaction or operation requires the intimate contact of gas and liquid it is generally more satisfactory to disperse the gas through the liquid phase than the reverse. Exceptions to this rule are in those cases (combustion or drying), where it is necessary to bring a small amount of the liquid into large volumes of gas, and thereby to produce an unusually large surface area per unit quantity of the liquid.

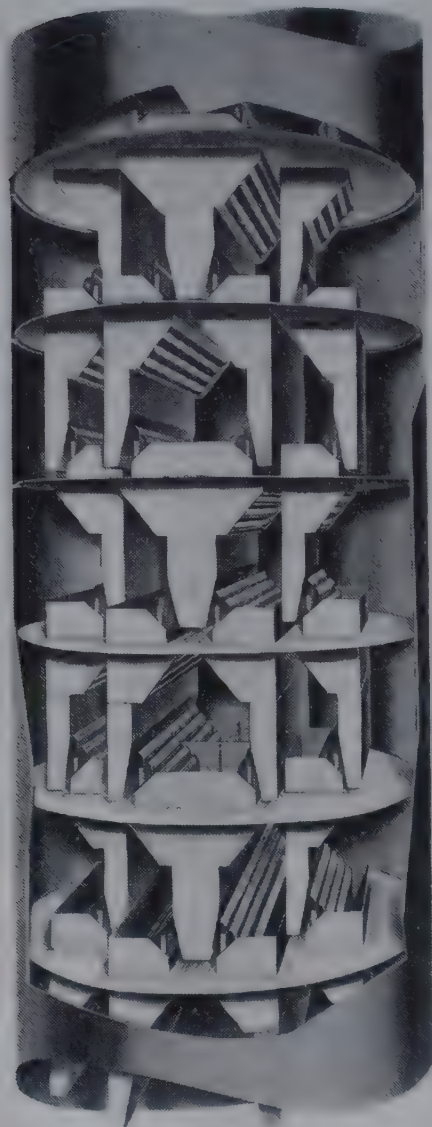
Mixing of Gases with Liquids of Low Viscosity

Batch Mixing. The mixing of gases with liquids as a batchwise operation is encountered frequently in chemical engineering practice. Probably the simplest of all methods of mixing a gas with a liquid is to introduce the gas at the bottom of the tank containing the liquid and to permit it to bubble up through the liquid. A sparger pipe or fitting to break up the gas into fine bubbles and to distribute them more or less uniformly over the entire horizontal cross-section of the liquid improves the contact. If the time of contact between liquid and gas is too short in a single pass, the tank may be closed and the gas collected at the top, drawn off by a pump, and reintroduced (with fresh make-up gas) at the bottom of the tank. Additional contact area can be obtained by simultaneously removing liquid from the bottom of the tank and spraying it into the gas space at the top.

Mechanical agitators are also used to distribute gas throughout a liquid. A closed-vane turbine mounted on a hollow vertical shaft can be used to draw gas down through the shaft and discharge it horizontally into the liquid. The liquid is simultaneously agitated by the turbine impeller. Fresh gas can be introduced to the gas space above the surface of the liquid or through a separate gas inlet bubbler near the bottom of the tank.

Continuous Mixing. A gas is frequently blended with a liquid by introducing the two simultaneously to the inlet of a centrifugal pump. Where a single pass does not provide sufficient contact time, often two or three pumps in series will produce the contact required. The aspirator is another ideal pump for introducing gas into a liquid. Either the gas or the liquid may be used as the activating fluid in the jet of the aspirator with the other fluid being drawn into the stream.

A mechanical mixer of the turbine type, the so-called *turbomixer*, can be used for continuous blending of gases with liquids. This mixer provides a series of mixing compartments through which the liquid is slowly passed. It is brought into contact with new gas bubbles in each compartment. Liquid may be passed upward or downward through the unit.



(Koch Engineering Co.)

Figure 68. Cascade Tower.

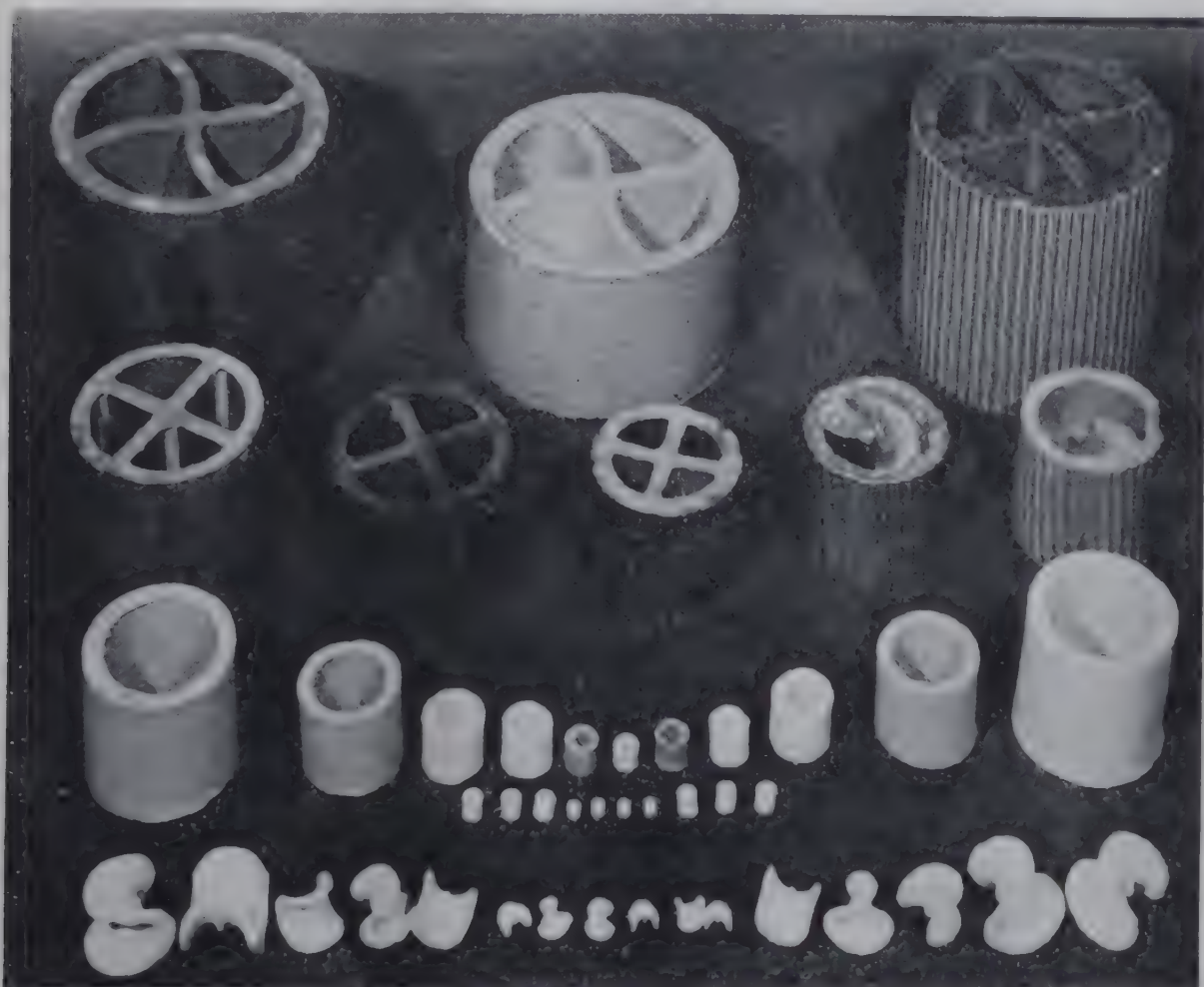
There are several types of towers in which liquid and gas are brought into contact by spreading the liquid out into thin layers, by dispersing it in small droplets which fall through the gas, by repeatedly breaking up the gas stream into small bubbles as it passes upward through the liquid, or by various combinations of these methods.

The *wetted-wall towers* are designed to spread the liquid into thin layers, agitate it well, and at the same time interfere as little as possible with the passage of gas through the tower. Various types of plates, cones, or open grids are used to cascade the liquid from one surface to another as it courses downward through the tower.

Liquids are often introduced as a fine spray into the top of empty towers, thus providing good contact with a stream of gas by the time the droplets reach the bottom of the tower. Spray falling on the walls gives a wetted-wall effect at that location.

Packed towers are probably the most widely used equipment for mixing gases and liquids. These towers are simply tall cylindrical tanks, or medium or large diameter pipe, having a grating near the bottom to support the packing, and packed with any

rigid substance which will spread the liquid into many small streams. As the gas ascends the column, it too, is broken up into numerous small streams which mix with the liquid flowing counter to it.



(Maurice A. Knight)

Figure 69. Tower Packing Shapes.

Tower packing is made in numerous forms. It may be a random filling of pieces of broken tile or brick, or of manufactured filling materials such as Raschig rings or Berl saddles. It may also be packed with specially constructed wooden grids, precisely stacked with brick of either regular or special shape, or filled with carefully placed Raschig rings (spiral or plain) or other special designs of packing material. The special packing materials, when carefully stacked in the tower, give the best contact with the least pressure drop; but their installed cost may be several times that of random filling of even manufactured shapes. Manufactured

shapes* will give much better service than broken tile filling but at higher first cost.

There are several towers in which the gas stream is repeatedly broken up into small bubbles. These are the various kinds of perforated- or bubble-plate towers, the most popular of which is the bubble-cap tower.

The *perforated plate* (sieve plate) tower has a series of horizontal plates equally spaced in the column shell. The plates are perforated with numbers of small holes distributed over the plate surface. The velocity of the gas passing upward must be great enough to retain a certain amount of liquid on the plate. The plates are sometimes constructed of wire screens.

Bubble cap towers also have a series of equally spaced horizontal plates in the shell. A mass of liquid is held on the plate by an overflow pipe projecting several inches above the plate. This pipe extends downward beneath the liquid surface on the plate next below to prevent short circuiting of the gas stream. Instead of perforations, each plate has a number of short pipes, surmounted by a slotted cap. The slots are below the liquid surface. As the gas passes upward from plate to plate, it is forced through the slots and dispersed through the liquid as streams of fine bubbles.

Mixing of Gases with Liquids of Medium Viscosity

The mixing of gases with liquids of medium viscosity (up to those having the consistency of heavy syrups or pastes) is somewhat difficult. Techniques such as those of bubbling the gas through the liquid or of passing the liquids through either a packed tower or a bubble cap tower are not practicable for this requirement.

Units such as the turbo-mixer, one of the wetted wall towers, the spray tower, or even pumps of several styles may be used as blenders for gases and heavy liquids. Whippers or beaters (similar in construction to the domestic egg beater), which either fold gas into the liquid by having the stirring elements lift up and out of the liquid mass or churn the gas into the liquid by pulling it between rapidly rotating blades, are very useful for mixing gas with a very heavy liquid mass.

A widely used technique for contacting a gas and viscous liquid consists of spreading the liquid in a thin layer over a moving surface and passing the gas over this material.

Mixing of Gases with Liquids of High Viscosity

It is virtually impossible to incorporate a gas in a plastic or semiplastic mass such as rubber, a heavy tar, or materials of that consistency, and yet many products on the market are solidified foams. These foams are ordinarily formed by mixing gas-generating substances in the material when it is in the plastic state. When the gas is generated by application of heat, the foam is produced; it is hardened or cured by further treatment.

Virtually all devices which are at all successful for mixing a gas with a very viscous liquid are batch machines.

Whipping machines, if made powerful enough, will fold and incorporate a gas into light plastics. In the event the liquid is so heavy that these units will not function properly, a kneading device is usually required. This unit, a very powerful and sturdy mixer, is so arranged that the material will be cut or torn, stretched and folded, thus incorporating gas into the mixture. The several patterns of kneader are discussed in a section dealing with liquid mixing.

Mixing of Liquids with Liquids. If liquids to be blended are of low viscosity, have nearly the same specific gravity, and are mutually soluble, complete mixing is very easily attained. If the opposite situation holds, mixing may require powerful mechanical devices, expensive to buy and operate. The techniques employed in the mixing of liquids involve materials of widely different properties, and the machinery therefore is quite variable in design.

Mixing of Liquids of Low Viscosity

Batch mixing. Two liquids, introduced together into a tank or reaction vessel may be mixed by high- or low-speed mechanical agitators, by outside circulation or by air agitation. Two general types of high-speed agitators are available, both quite suitable for the mixing of low-viscosity liquids. The most popular are the several styles of *propeller mixers*. The propellers may be introduced into the liquid from the surface on a vertical or nearly

vertical shaft, or may be attached to a shaft which is led into the tank through a fitting on the side of the tank. The shaft of the side-entering installation may be radial in position, or may angle upward or downward, or to either side of the true radial position. Mixing is greatly facilitated by using more than one propeller, either two or more on the same shaft or a similar number on different shafts. Propellers traveling at different speeds, in opposite directions, or having different pitches will further improve the agitation of the liquid in the tank. The major object of the various patterns is to prevent swirling of the entire contents of the vessel, and to bring the denser liquid on the bottom into contact with the lighter liquid at the top. A propeller located at the bottom of a submerged draft tube usually promotes excellent stirring of the contents of the vessel.

The second general type of high-speed agitator is the *turbine mixer*. This mixer has an impeller which is rotated at a reasonably high speed inside a stationary deflecting-blade ring. The mixer is made more effective by placing a screen or punched plate in a ring just inside the stationary blade section. For still further improvement two or more impellers are mounted on a single shaft.

The main disadvantage of the high-speed mixers of any type is their high power requirement. For an operation requiring rapid mixing and good blending of immiscible liquids of somewhat different densities, the use of a high-speed mixer is almost essential.

Slow-speed agitators are built in a number of designs. Most of them are variations of the ordinary *paddle mixer*. The simple paddle mixer, horizontal, single-arm or double-arm, vertical or gate types all tend to swirl and stratify the contents of a tank, thus defeating the general objective of drawing the two liquids together. Stationary fingers intermeshing with the agitator, which can be used with any but the gate type of paddle mixer, break up the swirl and improve the mixing action materially. Even small flat projections extending from the walls of the tank help to break up swirling.

The *double-shaft mixer* is another paddle-type mixer which overcomes the problem of swirling and yet permits the withdrawal

of the entire mixing element for ease in cleaning. This mixer, by having two shafts, one as a tube surrounding the other, can have paddles attached to both shafts, and thus be driven in opposite directions.

The paddle mixers do not disperse material as effectively as do the high-speed agitator types, and it is likely that the total power for a given dispersion is somewhat higher with the low-speed mixer than with the high. However, if it is desirable to maintain a suspension of one liquid in another for an extended period of time, the slower, lower-powered mixers are usually quite satisfactory.

Two liquids can be mixed effectively by withdrawing the heavier liquid from the bottom and spraying it into the top of the tank, vice versa, or both simultaneously. A superior mixing action can be obtained by withdrawing the less dense liquid from the top and pumping it through an aspirator located in the bottom of the tank. Thus liquid from the bottom of the tank is pulled into the stream of liquid being pumped, and is mixed thoroughly with the lighter liquid before the mixture is released into the main body of liquid in the tank.

Mixing of two liquids by air agitation is possible. This technique may take one of two forms. The air may simply be introduced from a *sparger pipe* in the bottom and produce agitation as it passes upward through the liquids, or it can be introduced into the bottom of an *air lift*, and cause internal circulation of the liquid as well as agitation.

Continuous mixing. The continuous mixing of two streams of liquids of low viscosity can be effected in several ways. (1) The two liquids, like a gas and a liquid, can be brought together at the intake of a centrifugal pump or series of centrifugal pumps and mixed by the violent action within the pump. (2) The liquids may also be pumped together through a baffle-plate column somewhat similar to those used for mixing two gases. The rapid changes of direction as the liquids pass around the baffles create highly turbulent conditions in the liquids. (3) Multi-compartment mixers, in which the two liquids are led from compartment to compartment, and agitated thoroughly by means of a turbine or propeller mixer in each compartment are also widely used.

A special continuous blender for liquids of low viscosity has been recently developed. This is the so-called *homogenizer*, which will give such a finely divided dispersion of one liquid in another that fairly stable emulsions are formed. In one pattern of homogenizer the liquids are dispersed by forcing the two liquids together through a spring-loaded globe or plug valve, the pressure required to open the valve and permit the flow of liquids being about 1,000 psi.

Mixing Liquids of Medium Viscosity

The mixing of two liquids of syrupy, pasty, or grease-like consistency may provide major problems in agitation. The air agitators, and the high-speed turbine or propeller type of agitators are not suitable, in general, for use as mixers for this class of material.

In addition to the regular paddle-type mixers, there are the several modified types of paddle mixers used almost exclusively for liquids of high viscosity. These are powerful machines arranged to travel at slower speeds and designed for closer meshing of blades than the agitators for thin liquids. Since swirling is not serious at the speed of these mixers, and since the stationary fins or fingers would create pools of stagnant material, the mixing vessels are usually smooth on the inside.

The problem of thick liquids depositing on the walls of the vessel out of range of the mixing paddles is partially solved by shaping the paddle blade so as to just clear the inside walls of the vessel, or to have it actually wipe the walls as it turns.

The *pony mixer* is a paddle mixer of special design for mixing pastes in small-to-medium size batches. In this unit the agitator is offset in the container and mixes either by a planetary motion of the agitator or by the container being slowly rotated while the agitator turns on a fixed shaft. The *angular mixer* is a new and special model of the pony mixer. In this design the shaft enters the mixing tub at an angle from the vertical.

Ribbon mixers, more commonly used as dough mixers, find limited application in the mixing of liquids of fairly high viscosity. This mixer, while built in a variety of patterns, consists essentially of a helical ribbon which rotates in one direction around a

screw impeller or a second helical ribbon rotating in the opposite direction.

The *revolving-cone mixer* consists of one or several hollow truncated cones rotating about a vertical axis. Vanes fastened to the inside of the cones propel the material through the machine.



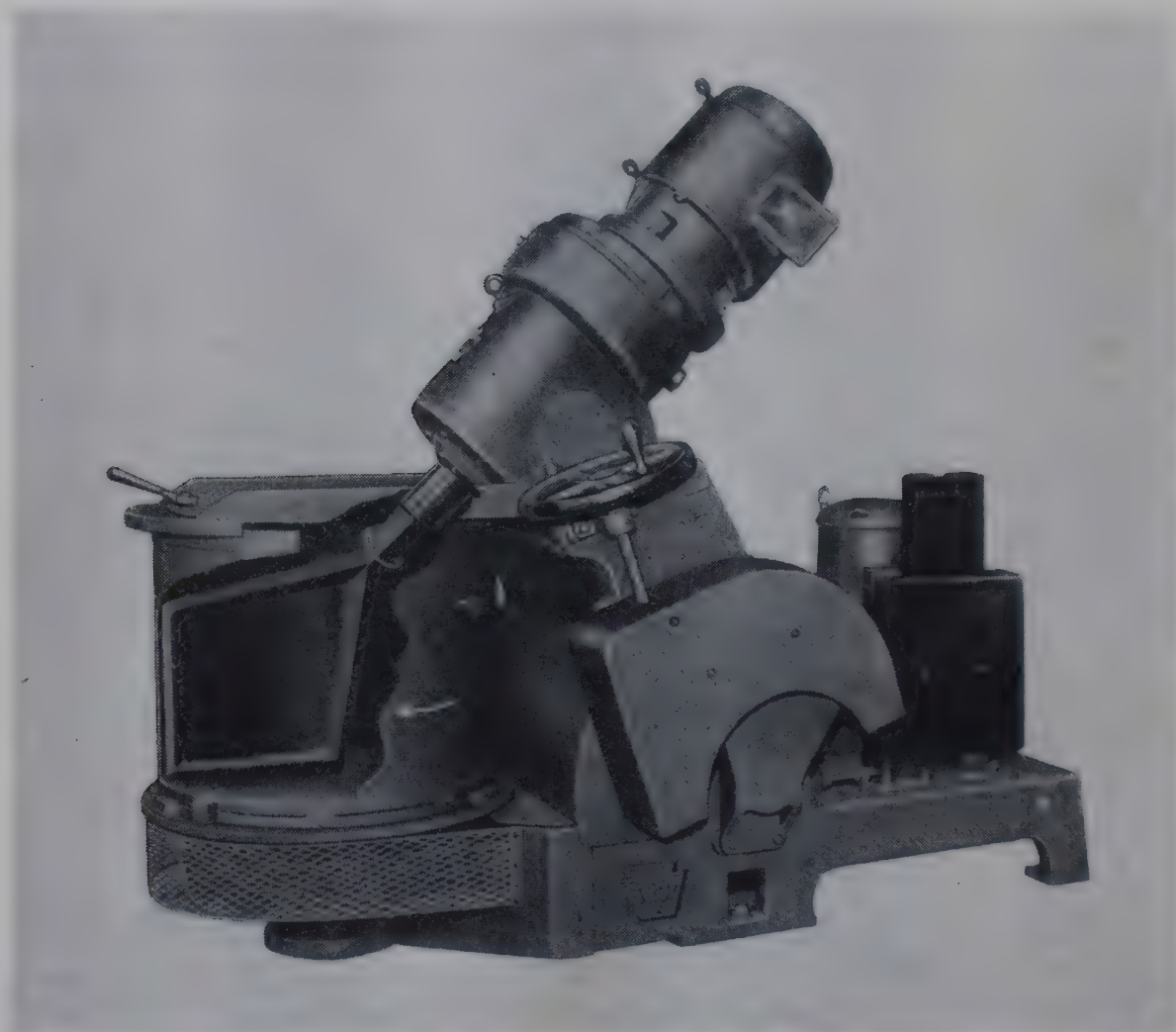
(Buřlovak Equipment Div. of Blaw-Knox Co.)

Figure 70. Agitator.

Mixing Liquids of High Viscosity

The problems involved in the mixing of liquids of such high viscosity that they are semi-solid or plastic in character are likely to be difficult to solve. Any mixers used with such materials must be exceedingly powerful. Several of the mixers for medium viscosity liquids can be adapted to the mixing of fairly heavy plastic masses. Notable in this group are the pony mixers and those of the horseshoe or scraper types.

Liquids too viscous to be handled in these mixers must be treated in a *kneader*. There are several styles of kneaders, the most popular general-purpose machine being the *Werner and Pfleiderer* type. This machine, which is made by several manufacturers, consists of two kneading bars which rotate horizontally in half-cylinder depressions in the bottom of the mixer. The machine



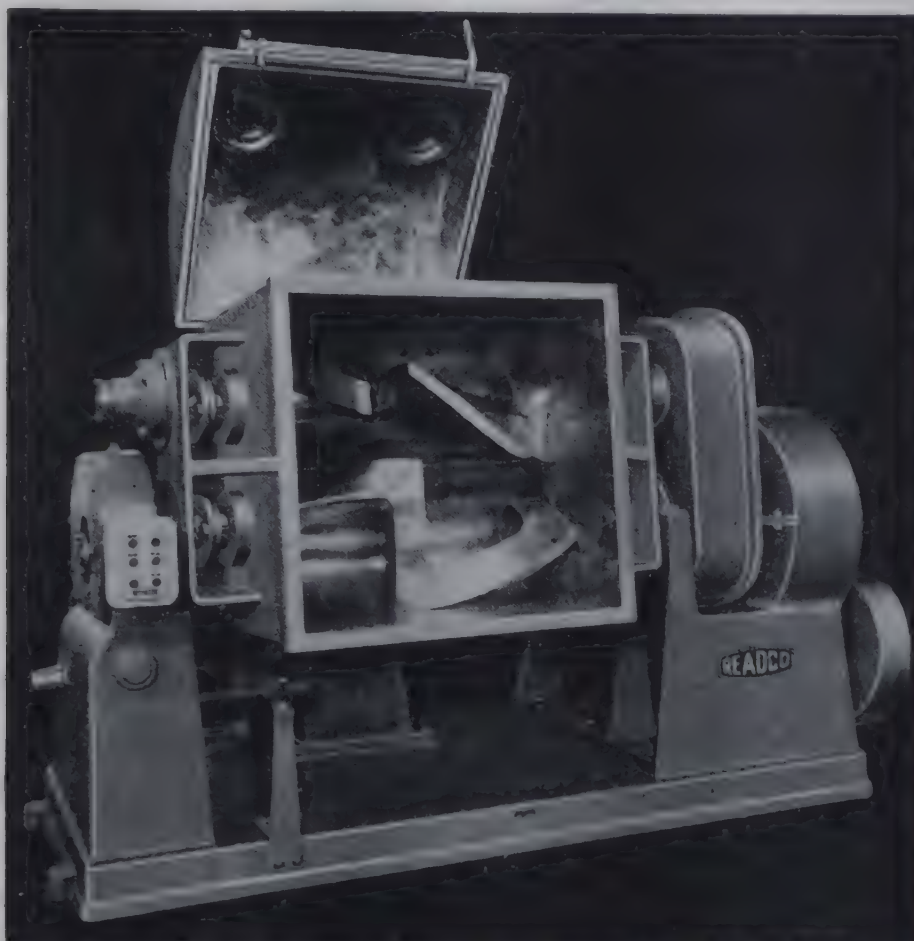
(Troy Engine and Machine Co.)

Figure 71. Angular Mixer.

operates by cutting the material against the saddle between the half cylinders, and by tearing, stretching, and folding the plastic material as the bars move through the mass.

The *Banbury mixer* can sometimes be used to mix plastics and rubber-like materials having viscosities above those handled in the bladed kneader. This machine, a masticator, works the material by squeezing and folding it between heavy spiral-shaped blades.

The *roll mixer*, used primarily for compounding rubber, consists of two steel-surfaced rolls adjusted to leave a small gap between them as they rotate. The rubber or plastic is caught between



(Read Standard Corp.)

Figure 72. Kneader. Werner and Pfleiderer Type. Bowl tilted to discharge position to show mixing blades.

the rolls and masticated as the rolls, traveling at different speeds, squeeze it between them. The mass collects on the slower-moving roll and is slit off from time to time, folded and reintroduced to the feed space between the rolls.

Many plastics mixers are provided with steam or water jackets around the body of the mixer and with water-filled cavities in the mixing elements. This jacketing has several functions. If the temperature must be controlled, or if a reaction is proceeding with the mixing, heat may have to be removed from the mass as a result of the heats of reactions or the heat generated by mechanical work done on the mix. Further, if the material can be heated even mildly without damage, the viscosity can sometimes be

greatly reduced by raising the temperature, thus materially reducing the power and time required for the blending operation.

Mixing of Solids with Liquids. The mixing of solids with liquids in such proportions that the final mass is liquid rather than solid in character can usually be accomplished by the same techniques used for mixing liquids. The viscosity of the liquid phase is generally the determining factor in the choice of the mixing machine. However, in some mixes the presence of the solid phase, even in very small amounts, may very markedly raise the apparent viscosity of the mass, and although the material may be suspended in a liquid of low viscosity, the presence of the solid may produce such a thick paste that it can be handled only in a kneading machine. To meet this problem it is sometimes quite advantageous to start the mixing operation in a low-viscosity mixer and transfer the material to a kneader for the final addition of solid material.

The techniques for mixing solids with liquids are essentially the same as those used for the mixing of two liquids. In addition, several methods are used widely for liquid-solid mixing and yet are little used for liquid mixing, even in the heavy plastic range.

Mixing of Low-viscosity Mixes. Mixing techniques making use of turbo-mixers, high-speed propellers, or turbine mixers are seldom applied to the mixing of solids and liquids. Erosion on the rotating elements and on the walls, troublesome enough with liquids alone, is often greatly increased if solids are present.

Most general-purpose mixers for thin mixes are of the ordinary medium- or slow-speed paddle types, either with or without stationary fingers, and with either single- or double-motion paddles. Large-scale mixing is sometimes accomplished by mounting several rotating paddle mixers on a beam which can be moved from end to end of a rectangular tank, or around a central axis in a circular tank.

The *air-lift agitator* is also useful for light slurries. The tank for air-lift solid-liquid mixing should have some means, such as a rotating plow or a conical bottom, to direct any solid which settles toward the intake of the air lift.

The familiar *cement mixer* is an excellent and cheap mixing

device, widely used for mixing solids and liquids, and yet not often used in strictly chemical operations.

The *colloid mill* is a specialized mill for making extremely fine suspensions of either solids or liquids in a liquid. This device corresponds to the homogenizer for liquids, but is more versatile since it is capable of preparing either emulsions (liquids-in-liquids) or suspensions (solids-in-liquids). The materials are mixed as they pass between a rapidly revolving solid rotor and its solid casing.

The *ball mill* can be used to obtain very thorough mixing of solids and liquids. Semi-colloidal dispersions can readily be prepared, the mill acting simultaneously as a grinder and mixer. The main disadvantage is that it is extremely difficult to clean.

Mixing of Heavy Solids-in-Liquid Pastes. Heavy pastes are similar in character to the viscous liquids and can be mixed by the use of similar techniques.

The *roll mill*, particularly the multiple-roll type is widely used for the mixing of materials like printing inks and paints.

Mixing of Solids in Heavy Plastic Masses. The techniques for incorporating solids into a plastic mass are the same as those used for mixing plastics with any second material. The mixing is usually done in small batches, and the time and power requirements are both excessive.

The ceramic industry has developed one of the few mills for handling heavy plastic masses which can be considered to be continuous. This is the *pug mill*. This mill faintly resembles the Werner and Pfleiderer mixer. In the pug mill, however, the shafts are larger, and the paddles are converted into short heavy blades. The blades are tilted slightly so that as the shafts rotate the material is moved along as in a screw conveyor, being cut, squeezed, and mixed as it progresses through the mill.

Mixing of Materials with Solids

Most of the mixing operations involving solid systems are those concerned with mixing two or more solids. To get intimate mixing, the solids must be finely ground. Mixing of solid powders is far simpler and less expensive than the mixing of either viscous

liquids or pastes. The mixing of either a gas or a liquid with a solid is also often required.

Mixing of Gases with a Solid. A process or reaction requiring the mixing of a gas with a massive solid (any particles retained on a 60-mesh screen) can be carried out using one of several different techniques.

The most obvious technique, and certainly the simplest, is that of placing lumps of the solid in a vertical tower, and passing the gas through the mass. This technique, in general, might be compared to the older methods of burning lump coal, in which fresh coal was distributed at intervals over a fuel bed to which air was admitted from the bottom. This technique is quite satisfactory if the reaction speed is high enough to permit reasonably complete reactions of the solid and gas in the relatively small contact area available per unit mass of the solid. Many physical and chemical operations are carried out by passing gases through fixed beds of granulated or lump solids.

The difficulties which may be encountered in this operation are similar to those obtained with any packed column: plugging of the column in certain areas, channeling in others, and the considerable pressure often required to force the gas through the bed are probably the most troublesome.

If the solid is finely divided, or if it is close to its softening point, the pressures required to force the gas through the solid may be excessive and channeling may be especially pronounced. To overcome these difficulties, the solid is often mechanically agitated while the gas is passed through it. It is usually best to pick up the solids and spill them through the gas stream; mixers of the tumbling barrel or kiln type are best for this purpose.

Many processes may require a gentler handling of the solid material to avoid mechanical damage to it, and still require contact of gas with the solid in some technique other than the use of the packed tower. To meet this problem, the solids may be spread in thin layers on trays, slowly moving belts, or other surfaces over or through which the gas may be circulated. A similar technique is to stack the material in loose piles, either stationary or on cars, and pass the gas through them.

The newest technique for mixing gases and solids is that

of the *fluidized bed*. The solid is reduced to granules which are suspended in a slowly moving vertical stream of gas. The bed, instead of being fixed, floats in the gas stream, and possesses all the attributes of a fluid. There is no tendency for channeling and the contact between solid and gas is excellent.

Virtually any of these techniques can, if necessary, be made continuous. The rotary tumbler, for example, can be tilted at such an angle that material will be moved from one end to the other. A helical projection fastened to the inside walls of the drum will accomplish the same result. The technique of thin-layer contacting can be made continuous by using a belt conveyor. The fluidized solid can be fed continuously to the bottom of the bed, and withdrawn from the top in much the same fashion as a liquid. Even the mixing of gas with a massive solid in towers is continuous if the solid is consumed in the action.

Mixing of Liquids with a Solid. The techniques for mixing a liquid with solids can, if the liquid is of low viscosity, be much the same as those described for mixing a gas and solid. The only technique not widely used is that of spreading the solid in thin layers and passing the liquid over it, although this too is feasible in certain areas of activity. However, trickling or pumping a liquid over a mass of granular solids held in a vertical tank or column; agitating a liquid and solid mass as can be done in a tumbling barrel or a cement mixer; or floating a granular solid mass in a liquid stream as a fluidized bed are all practical methods which are widely used. These can be made continuous with the same modifications as indicated for gas-solids mixing.

There is sometimes the necessity of adding barely enough liquid to a solid mass to wet the solid; this means that considerable working of the mixture must be done to distribute the liquid evenly through the mass. This can be done in a kneading machine. If the solid is granular and is not reduced to a plastic or dough-like mass, it can be mixed in a dry solids mixer. There is also one machine which is widely used for incorporating small amounts of liquid into a semi-solid mass. This is variously known as a pan mixer, *muller*, edge runner, or putty chaser. It consists of one or two large heavy steel or stone rolls, driven by a vertical shaft which rotates a spider carrying horizontal shafts passing through

the axis of the rolls. The rolls thus roll and slip over a pan which is under them and in which the material to be mixed is placed. The solid material is plowed into piles ahead of the rolls by means of curved scraper blades. Thus the solid is turned, squeezed, wiped, and ground simultaneously, and a very even-textured and uniform mixture is obtained.

Mixing of Solids with Solids. The mixing of two or more dry solids is accomplished easily in any one of a number of machines designed specifically for the purpose.

The *tumbling barrel* is a simple, well-known and widely used device for mixing solids. This is simply a closed drum into which the solids are introduced through a quick-acting, dust-tight port in the wall of the barrel. The barrel rotates on a horizontal shaft mounted on the axis of the barrel.

There are various modifications of the tumbling barrel. For example, longitudinal bars on or close to the inside surface of the drum, or a polygonal rather than a cylindrical shape prevents the solid material from slipping on the inside surface of the drum, and promotes more rapid and effective mixing.

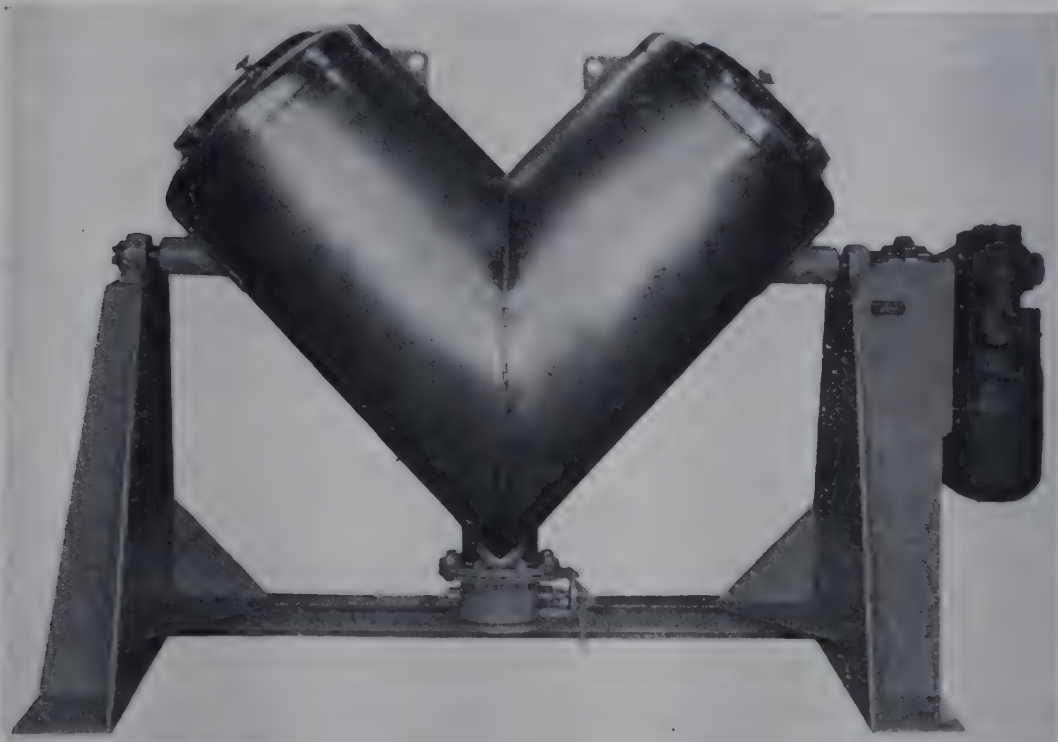
The oblique barrel, the double-cone mixer, the twin-shell mixer, and the cement mixer are some of the many variations of the simple tumbling barrel. All are suitable for general-purpose mixing of solid materials. The cement mixer, which is usually open, is not suitable for dusty materials.

A technique related to the tumbling barrel is the use of the ball or rod mill for the simultaneous blending and grinding of two or more granular solid materials.

Paddle mixers are used in many solid-solid mixing operations. Vertical paddles operating from a horizontal shaft in a horizontal cylindrical-bottom container, or in a totally enclosed drum give very good mixing. Sometimes the drum is provided with vertical fingers or knives, by which mixing can be combined with the shredding of fibrous materials, such as rags or paper.

Paddle mixers of the pony type are satisfactory if the solids are light-bodied. A rotating pan with stationary plows is sometimes used for blending dry materials. Ribbon or helical mixers are also used to some extent for dry mixing. Mixers somewhat similar to the kneaders are also useful.

Most of the mixers so far described are batch mixers. The rotating pan and plow mixers can be made continuous by placing several units vertically one above another, and by arranging the plows in such a manner that the material is plowed from the center toward the outside on one tray and from the outside toward



(The Patterson-Kelley Co., Inc.)

Figure 73. Twin Shell Dry Blender.

the center in the next and so on through the machine. The barrel mixer can be made continuous by elongating it and tilting it slightly from the horizontal, or by adding a helical flight on the inside. Even the paddle mixers can be used to move material along the bottom of the shell as the blades plow through the solid mass.

A fairly satisfactory continuous mixer for solids is a specially constructed screw conveyor. This machine with cut-and-folded flights or with intermediate paddles will do a reasonably good continuous mixing job.

13 : REACTION VESSELS

Techniques for the Conduct of Chemical Reactions

Reactions involving gaseous systems

Reactions involving liquid systems

Reactions involving solid systems

Electrolytic reactions

Every process involving a chemical reaction requires a vessel in which the reaction can take place. All tasks and the techniques required to carry them out are actually only auxiliaries to the major objective of promoting the reaction.

Laboratory reactions are normally conducted as small-scale, batchwise operations in glass or other noncorrosive containers in which agitation can be excellent, in which the progress of the reaction can be observed continuously, and which can be quickly heated or cooled to meet temperature requirements. To transfer reactions from the laboratory to the plant and increase output from grams per day to tons per hour in equipment which is not free from corrosion, in which agitation of the whole contents may be difficult if not impossible, which cannot be cooled or heated more than a fraction of a degree per minute, and in which the reaction may go to completion without once being seen by the operator, requires the most exacting design and operational skill, and a thorough knowledge of the techniques relating to the conduct of a chemical reaction on a commercial scale.

The selection or design of a reactor or of the reactor system of a plant is dependent on a number of factors relating to the materials and the process. Some of the more vital factors are as follows:

1. Physical state of the reactants and products at temperature and pressure of the reaction
2. The necessity or desirability of making the reaction continuous
3. The temperature at which the reaction takes place

4. The pressure at which the reaction takes place
5. The production or requirement of heat by the reaction
6. The production of by-products and the necessity for removing these or main products to allow the reaction to progress normally
7. The effect of diluents such as steam or of oxidants such as air on the reaction mass
8. Chemical characteristics of the reactants and products
 - a. Corrosive character
 - b. Toxicity
 - c. Contamination of waste water or of air by reactants or products
 - d. Flammability, explosive characteristics
9. Physical characteristics other than the physical state
 - a. Viscosity of liquids
 - b. Boiling point of liquids
 - c. Melting point of solids
 - d. Surface properties
 - e. State of subdivision of solid
10. Reaction kinetics
 - a. Speed of reaction
 - b. Catalysts and their effect on the reaction
 - c. Control of by-products or side reactions
11. Production required
12. Cost of purchase, installation, and operation
13. Availability of equipment.

TECHNIQUES FOR THE CONDUCT OF CHEMICAL REACTIONS

The techniques involved in carrying out a chemical reaction on an industrial scale depend largely on the physical state of the reactants or products, or both, the desirability or feasibility of conducting a continuous process, and the temperatures and pressures required for the reaction.

Reactions Involving Gaseous Systems

Reactions of Gases with Gases. The containers needed for gaseous reactions are usually quite simple, in that little agitation

is normally required, and reaction equilibrium is often quickly attained. It may sometimes be necessary to reduce the speed of a reaction between gases. The problems of transferring heat to or from a gaseous reaction space are usually less complicated than those related to reactions of liquids or solids. High pressures, or temperatures, or both, with or without catalysts are sometimes required to promote reactions between gases.

Continuous Reactions. Continuous reactions are nearly always sought in chemical plant practice, and since they are so easily achieved in handling gases, and usually so satisfactory, there is ordinarily little need for any other than a continuous process for a gaseous reaction. A common requirement of reactors for gases is that they must be closed in order to retain both reactants and products.

Occasionally reactions between gases will proceed smoothly with little evolution of heat and without the necessity of placing the system under pressure. These reactions can usually be conducted inside a mixing device such as a baffled column; or the gases can be mixed in a pump or aspirator and discharged through an ordinary pipe. It is not often, however, that heat and pressure effects are not manifested in a reaction between gases.

Certain gaseous reactions require temperatures of a magnitude obtained only by the electric arc. These gases may actually be led through the flame of an electric arc in order to reach these temperatures. Gaseous reactions which will proceed at lower temperatures often can be carried out satisfactorily in tubes heated from the outside.

Other reactions require a negligible amount of heat, or none at all, but do require that the gases be heated to a kindling temperature. The oxidation of ammonia, for example, progresses very rapidly and releases considerable heat. It does, however, require that the gases be raised to the reaction temperature before the reaction can start. The reaction is initiated by passing the gas over an electrically-heated platinum gauze held in a steel cylinder. Once the oxidation starts, the gauze is maintained at the correct temperature by the heat of the reaction.

The heat from many exothermic reactions is not great enough to damage seriously the metal of a container; hence they can be

conducted in a metal tube or similar container and the hot gases can be led away through tubes to heat exchangers or to air or water coolers. Many reactions, like the combustion of gases of high calorific value, may produce exceedingly high temperatures and may create difficult problems of reactor design. Water- or gas-cooled walls may be used to conduct heat out of a reaction vessel. External fins or vanes on the reaction vessel may help to keep it cool by conducting the heat away more rapidly. A large reaction space is often useful. Reaction temperatures can sometimes be lowered by using copious excess quantities of one reactant but this may cause other complications.

Reactions between gases which are reduced in volume upon reaction can usually be improved in yield and increased in velocity if maintained at a high pressure. Reaction vessels have been designed for pressures as high as 25,000 psi. For continuous reactions, these will generally be long forged-steel tubes. The reaction takes place inside the tubes. The problems of high-pressure reactions are greatly magnified if the reaction must be carried out at high temperatures as well as high pressures.

Batch Reactions. Reactions between two gases are rarely conducted as batch reactions. When this is done, a tank of adequate size and strength, with or without mixing devices, is suitable. Many gaseous reactions between gases proceed so rapidly that explosions may easily occur if the reaction is started in large bodies of the gas mixtures.

Gases are often compressed on a laboratory scale and transferred to a high-pressure apparatus, known as an *autoclave*, where the kinetics of a reaction are studied. Laboratory autoclaves, which can be enlarged to a commercial size, are of three general designs: the vertical stationary cylinder having a mechanical agitator, and the rocking or rotating cylinders in which agitation is provided by the movement of the whole assembly.

Reactions of Liquids with Gases. Besides the combustion of liquid fuels in air and certain organic reactions which are greatly facilitated by the liquid being sprayed into a gaseous system, there are few commercial applications of the reactions of a liquid in an essentially gaseous system.

The same general observations which were made with respect

to gaseous reactions apply to reactions involving a finely-divided liquid spray dispersed in a gaseous phase. The same techniques are applicable to both. There is probably no case, however, where a reaction between a liquid spray and a gas is conducted as a batchwise operation.

Reactions of Solids with Gases. The reactions of a powdered solid dispersed in a gas are conducted by techniques similar to those used for other gaseous reactions. Unless the reactions involving a fluidized solid and a gas are considered as belonging in this group, there are few reactions between a finely-divided solid and a gas conducted in a gaseous system, with the exception of the large-scale combustion of powdered coal.

Reactions Involving Liquid Systems

The great majority of chemical reactions take place between liquids, or between liquids and gases or solids. Even several of the reactions involving materials which are normally solid are conducted at temperatures at which the solid materials become fluid and hence can be treated as liquids.

Reactions of Gases with Liquids. Most of the techniques concerned with the reaction of gases with liquids are dependent on the speed and relative ease with which the reaction proceeds. Some reactions between a gas, even in low concentrations, and a liquid are so rapid that they can be effected in an open tank merely by bubbling the gases through the liquid. Other reactions of gases with liquids are quite slow, due in part to the relatively low solubility of the gases in the liquid medium. These reactions can usually be aided by placing the system under pressure to increase the amount of gas dissolved in the liquid. Many reactions in this category also require the presence of a catalyst.

Continuous Reactions

Reactions at Ordinary Temperatures and Pressures. Gas-liquid reactions which will proceed at reasonable speeds without the production of excessive amounts of heat, or requiring no more heat than can be easily supplied by warming the liquid or gas, or both, are frequently encountered and are very easily conducted. Almost any of the devices designed for the continuous

mixing of gases and liquids will serve satisfactorily as reaction vessels. These include wetted wall towers, packed columns, bubble cap columns, cascade columns, turbine mixers, and many others. The consistency of the liquid, which is the controlling factor in the design of the mixers, is likewise one of the most important factors in the use of any mixer as a reactor for gases and liquids.

Reaction temperatures can be regulated by internal coils or integral jackets, or by circulating the liquid and gas, either before or during the reaction or both, through external heat exchangers. The latter practice is gaining in favor because of the better control it provides.

A continuous reaction between gases and liquids usually requires that the units be fed with gas and liquid at the proper rates in countercurrent streams. Since most reaction vessels for gases and liquids are vertical, this means that the liquids are introduced at the top of the tower and pass downward against the stream of gas which is introduced at the bottom and passes rapidly upward through the liquid. This method of contacting the reactants is usually to be preferred, since the most concentrated gas comes in contact with the liquid nearest equilibrium concentration and both solution of the gas and subsequent reaction are thus expedited. In some rare cases, however, parallel flow is desirable; to meet this requirement gas and liquid are usually introduced at the bottom of the unit and rise through the unit more or less together.

Reactions at Elevated Temperatures or Pressures. An increase in the concentration of the gas in the liquid, and therefore, an increase in the reaction rate, is often obtained by raising the pressure on the system. Reaction rate is also increased by raising the temperature; sometimes heat levels well above normal atmospheric temperatures are necessary for a reaction to proceed with any appreciable velocity. As the temperature is increased, however, gas solubility is decreased, and this effect may almost neutralize the advantage gained by increasing the temperature. Hence, in almost any case involving the reaction of a gas in a system essentially liquid, when the temperature is raised it is desirable, and quite frequently necessary, to increase the pressure on the system also.

If noncorrosive materials are being reacted, any of the continuous units for mixing gases with liquids, if made with sufficiently heavy walls, will serve for reactors operating under pressure. Fortunately, excessively high temperatures are not too often required, although it is not unusual for some reactions to require temperatures in excess of $1,000^{\circ}\text{F.}$, and pressures of several hundred pounds per square inch. For such severe service it may be necessary to use special steel alloys for the walls of the reactors.

The corrosive properties of certain gases and liquids cause the major difficulties in the design of high-pressure and high-temperature equipment. Some corrosive substances can be handled readily in ceramic tile or glass at room temperatures and low pressures, or in steel lined with lead, glass, plastic or rubber. All these materials are unsatisfactory for high temperatures, however. The difficulty of procuring a corrosion-resistant reaction vessel at a reasonable price, or sometimes at any price, makes some chemical products very expensive.

Batch Reactions

Although modern industrial design favors the use, wherever possible, of continuous operations, a number of reactions involving gases and liquids either are conducted on such a small scale that it would not be practicable to operate continuously, or else certain factors, such as low reaction velocity, would not permit the reaction to be carried out in any but a batch process.

Equipment for conducting a batch reaction of a liquid and gas can be quite simple. A closed vessel is required, and frequently the agitation created by introducing the gas through an opening in the bottom of the vessel is sufficient to assure satisfactory mixing of the materials. Operated as a batch unit, the gas is normally withdrawn from the top of the reactor, passed through a pump, and reintroduced at the bottom under the liquid. Fresh make-up gas is added as required. The liquid also can be circulated simultaneously and sprayed through the gas space as it is reintroduced at the top of the reactor. Further improvement of the contact of gas and liquid can be obtained by the use of a mechanical agitator, such as the turbine agitator.

Any one of the towers is often used for batch gas-liquid reactions. They are installed in conjunction with tanks for the liquid or gas, or both, and the liquid and gas are circulated from the tanks, through the tower, and back to their respective storage tanks until the reaction is to be completed.

High pressures and high temperatures are usually somewhat easier to maintain in batch equipment than in the continuous types. Reaction rates can be regulated somewhat more easily, and heat either to or from the reaction mass can be controlled much more readily in the batch-type reactor. The equipment required for high-pressure and high-temperature batch reactions includes autoclaves, bombs, or pressure vessels.

Reactions of Liquids with Liquids. When gases, or highly volatile liquids are not part of the reaction mass, either as reactants or products, the conduct of the reaction is much simplified. Seldom is a pressure much greater than atmospheric required. The tanks in which a reaction takes place can be open to the atmosphere, thus facilitating the introduction of reactants and the use of agitators. In the event the reactants or products develop any appreciable vapor pressure at the temperature of the reaction, it must be conducted as if it were a gas and liquid reaction mass, i.e., in gas-tight equipment. Further, even though the vapor pressure itself may be low, if the contents are toxic, or give off obnoxious fumes, even in small amounts, or if the reactants or products are hazardous or are affected by exposure to the air, gas or vapor-tight equipment may also be necessary.

Continuous Reactions. Since liquid reactions are often slower than those of gases, or even of gases and liquids, a continuous process may be somewhat more difficult to achieve. Contact time in a continuous reaction unit, while not specifically limited, normally tends to be short.

However, some reactions between liquids are rapid enough to be completed in the contact time which can be readily obtained in continuous equipment. Reactors for these processes often take the form of long baffled pipes through which the liquids can be pumped together, preferably mixed in a centrifugal pump used for circulation of the liquids. This type of operation requires parallel flow of the liquids, which must be suitable for the reaction.

Where countercurrent flow of reactants is desirable or essential, vertical units must be used, with the heavier liquid introduced at the top, the lighter near the bottom, with one liquid passing through the other. Sparger pipes or heads are used for each liquid so as to break it up into droplets. The introduction of each liquid is made a short distance from the ends of the reactor so as to allow a space for the collection and withdrawal of the individual liquids. Tower reactors are sometimes more than 100 feet in height in order to give sufficient contact time without the necessity for recycling.

Improved performance, with either parallel or countercurrent flow, can be obtained in most cases by the use of internal mixers in the reactors.

In a number of cases, particularly in the petroleum industry, quite high temperatures are required in a continuous process involving two liquids. This is easily achieved by passing the liquids through long tubes which are heated externally.

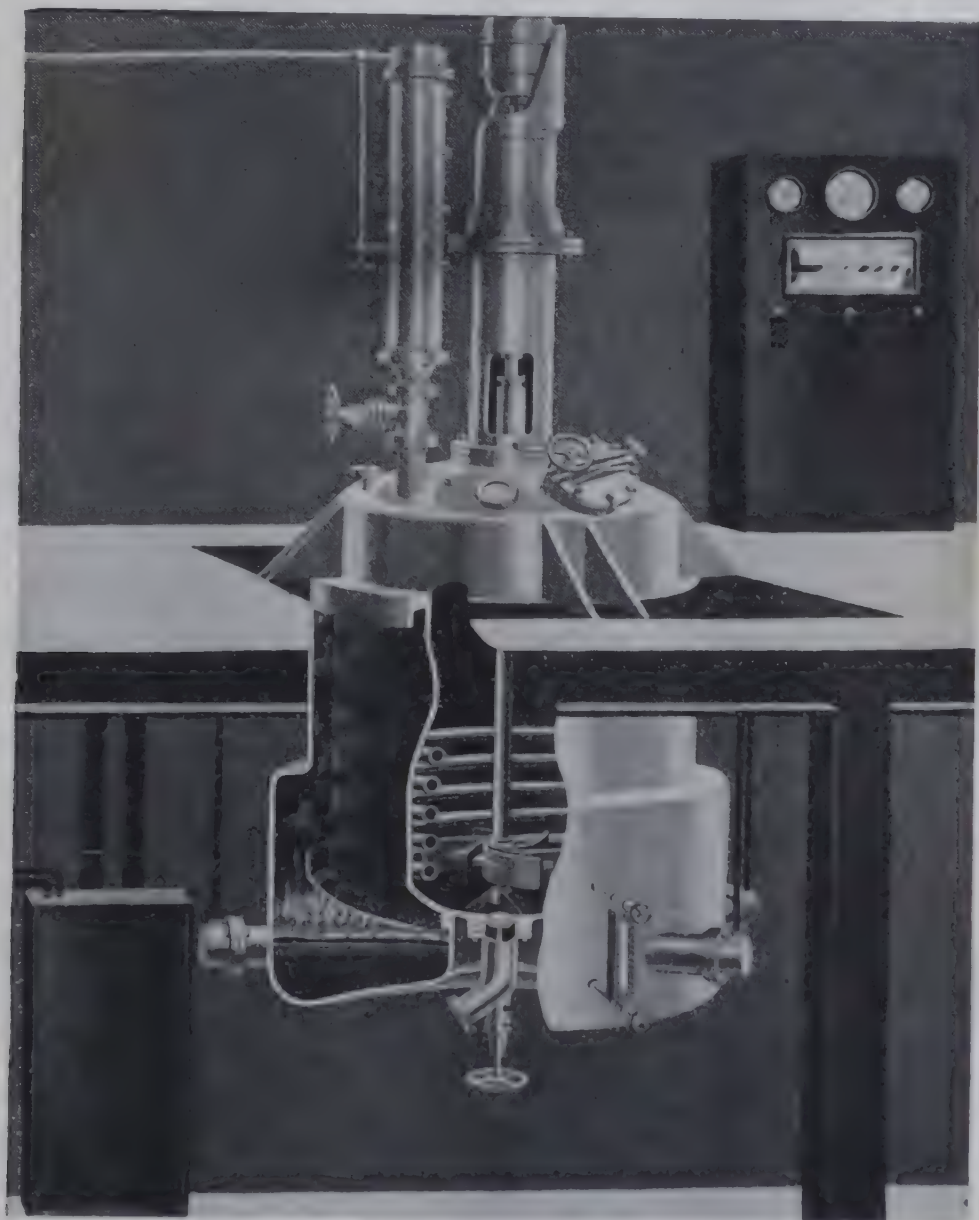
In high-temperature reactions between liquids, fairly high vapor pressures are almost always developed, and the reaction becomes in fact a gas-liquid system and must be handled and treated as such.

Batch Reactions. It has long been the practice in the chemical industries to conduct many reactions between liquids as batch-wise processes. It has been pointed out that many reactions between liquids simply do not progress rapidly enough to make continuous reactions practicable, and many products are made in such small quantities that continuous production is not profitable, even with its many advantages.

Since liquid-liquid reactions at atmospheric temperature and pressure are carried out so simply, batch reactors for liquids are the simplest of all reaction vessels, consisting of either open or covered tanks provided with proper agitation equipment. Since many of these reactions are conducted on a large scale the reaction vessels may be huge. Agitation is carried on by air, by steam, or by mechanical stirrers or various combinations of agitators.

Reaction tanks holding up to several thousand gallons at a batch, heated by steam or cooled by cold water or brine circulated

through jackets or coils, or both, and stirred by any of the various agitating devices are available. Reaction vessels are constructed of steel, stainless steel, aluminum, copper, and various



(Blaw-Knox Co.)

Figure 74. Jacketed Reaction Kettle, Electro-vapor heated.

alloys; steel clad with a corrosion resistant metal lining; steel or other metal coated with paints, plastics or materials of that character; or of wood, concrete, brick, tile or plastic.

There is some tendency in modern practice to replace the exceedingly large reaction vessel by a smaller reactor of the continuous type, and to recycle the liquids from storage tanks through the reactor and back to storage.

Enclosed low-pressure tanks are available for reacting liquids out of contact with the air, or for preventing noxious vapors or sprays from discharging into the atmosphere. Enclosed agitators or outside circulation provide the necessary mixing.

There are a few reactions involving liquids which must be conducted at temperatures ranging to 1,000°F. or more. To maintain materials in the liquid state at this temperature often requires the simultaneous application of considerable pressure. Steel reaction vessels constructed to withstand pressures of 1,000 pounds or more per square inch and temperatures up to 1,000°F. are available in fairly large sizes. Heat is usually supplied to reactions requiring high temperatures by circulating the liquid from the reactor, through an external heater, and back to the reactor. Reactions which must be conducted at pressures much in excess of 1,000 psi require the use of an autoclave.

Reactions of Solids with Liquids. Solid-liquid reactions in a system essentially liquid in character respond to the same general treatment as do completely liquid systems. The same situation holds for continuous or batch reactions, for reactions at high pressures and high temperatures, and for reactions of corrosive materials. Since it is more difficult to handle solids in a circulating system, the dual circulating system, as used in the two-liquid reaction, is not usually advisable. If a gas is used or produced in a reaction between a solid and a liquid, or if the liquid has a high vapor pressure, the system must be treated as if it consisted of a liquid and a gas alone.

Reactions Involving Highly Viscous Liquids. Few of the techniques used to promote the reaction of liquids with other liquids, or of solids or gases with liquids are useful if the liquid is plastic or semi-plastic.

The mixers which are required for blending plastic materials, or for adding solids to plastics, are usually the vessels in which the reactions of these materials take place. To the problems of blending are added those of heat transfer and temperature control. The latter, in many cases, is difficult to secure.

Scraper type, double-acting paddle agitators meet the requirements for fairly heavy liquids, or of thick pastes of solids and liquids. The positive scraping action of this mixer has an im-

portant function in temperature control. For heavier plastics, the kneaders, such as the dough mixer, the Werner and Pfleiderer mixer, the Banbury mixer, or the roll mill must be used. The first three are often jacketed for temperature control. The last three types may also have hollow agitators to provide additional temperature control.

Reactions in which very viscous liquids are involved seldom require the application of pressure. In those cases where pressure is required, both the Werner and Pfleiderer mixer and the Banbury mixer are constructed so as to permit the attachment of a vapor- or gas-tight lid, and are built heavily enough to withstand high internal pressures.

Reactions Involving Solids Systems

Reactions of gases or liquids with massive solids are frequently conducted without agitation of the mass. The reactions of two solids almost always require mixing during the period of reaction. Where agitation is not possible, unless the solid is consumed in the reaction with a liquid, gas or other solid, the reaction is nearly always batchwise.

One of the most difficult problems to solve in reactions involving massive solid materials is that of heat transfer and, therefore, of temperature control. When heat is generated in the reaction it is often removed by circulating an excess of the gaseous or liquid reactant through the mass, then to a heat exchanger, and back to the reaction unit. Where this is not possible, the problem is sometimes solved by adding an inert gas or liquid to the reaction system, and using this as a means of removing excess heat or of slowing down the reaction so heat may not be produced so rapidly.

In the many cases where heat must be supplied, the problem may be even more complicated. The most convenient means of conducting heat into the reaction space is to heat the gas or liquid entering the reaction to a temperature at which it will carry in enough energy as sensible heat to propagate the reaction. If heat requirements are too high to permit this, or if the temperatures required may promote side reactions in the gas or liquid, or develop excessive pressures, it is sometimes possible to

transfer sufficient heat into the reaction mass by means of a heated stream of inert gas or liquid, and to operate it as an intermittent reaction.

In many reaction masses the solid may be combustible and give off considerable heat upon reaction with air. Thus air may be conducted to the reaction space during a heating-up period, the heat evolved on combustion of some of the solid being stored as heat energy in the solid. The stored heat is then used during a reaction period. This is the well known water-gas reaction, in which coke is burned with air in the heating period, and the hot coke reacted with steam to produce the water gas.

Another method of bringing heat to a solid reaction mass, if the reactant is combustible, is to add just enough air to the reacting mass to produce heat in sufficient quantity to sustain the reaction. Combustible material can sometimes be mixed with the solid reactant and consumed by air passed through the unit, thus producing internally the heat required for the reaction. The several methods for bringing heat into the reaction mass profoundly affect the type of reaction vessel required. A serious problem which affects reactions of both gases and liquids with a massive solid is the plugging of equipment as the solid is disintegrated by the reaction.

Reactions of Gas with a Solid. The reactions of a gas with a massive solid are surprisingly frequent in industrial practice. For example, the combustion of coal on a grate is a gas-solid type of reaction. Similarly, the gas-producing reactions, such as the manufacture of producer gas and water gas involve a massive solid.

In many reactions between a gas and a solid, the solid is consumed to form gaseous or liquid products, and the heat requirements are such that they can be met continuously. These reactions can be conducted with greatest ease as continuous processes.

The reaction of the gas with the solid, if the latter is in a massive form, is usually conducted in a tower or vertical shaft in which the solid is placed in lump form, and over which the gas is circulated. Construction of the unit is dependent on the temperature at which the reaction takes place, and upon the corrosive properties of the gas or solid. Rarely is it necessary to increase the

pressure on a reaction of this kind. If it is, the reactor must, of course, be gas-tight and strong enough to resist the internal pressure of the system. The reactor is refilled with lumps of fresh material as the solid is consumed and settles in the reactor, or as the reacted mass is removed as a liquid or a solid from the bottom of the tower. If the tower is operating at pressures close to atmospheric the additional solid is added continuously or in small batches without interrupting the continuity of the reaction.

For the reaction to progress without difficulty it is necessary that the solid mass remain lumpy until completely consumed. If the solid tends to fuse, or if it disintegrates internally to a fine powder, the accumulation of such material in the solid bed will plug the reaction tower.

Finding or preparing a solid which will be satisfactory for use in this type of operation may be a difficult problem. Many substances are infusible and mechanically strong, and can be obtained free from internal faults or cracks so that reaction will not disintegrate the lumps. Other solids must be so prepared as to acquire these properties. For example, coal which tends to fuse has little use in the water-gas generator and may be much less satisfactory than coke in a producer-gas unit. Even coke has to be carefully prepared from a special type of coal to be strong enough to resist crushing in the blast furnace for pig iron production. Other solid materials may be briquetted or sintered to form a rigid clinker-like mass as a preparation for reactions with a gas.

Several other techniques for the continuous reaction of a gas with a solid are possible. The use of the traveling bed, such as the chain-grate stoker, in which the gas may be passed either upward or downward through a thin layer of solid, is common. The fluidized technique is becoming an increasingly important method for promoting the reaction between a gas and a solid. Another technique, somewhat older, is to suspend a finely divided solid in a nonreactive liquid and conduct the reaction as if it were a gas-liquid reaction in equipment designed essentially for that type of process.

Batch reactions between gases and solids are carried out in equipment much like that used for continuous processes except

that the solid, if not consumed, must be mechanically or manually removed from the reactor at the conclusion of the reaction. Batch reactions are useful in those cases where the short contact time of the continuous processes would not permit a reaction to proceed to completion, or where high pressure or vacuum are required. No completely successful technique has been developed for introducing a massive solid into a reaction space or removing one from it while the system is under considerable pressure. In a batch reaction, the solid is usually packed in a tower or other vessel and the gas is circulated over the solid until the reaction is complete.

Reactions of a Liquid with a Solid. The same general techniques can be applied to the reaction of liquids with massive solids as those used for the reaction of gas with a solid. The only technique inapplicable is the one in which another liquid is employed as a carrier for the solid.

As with the gas-solid reactions, solid material is placed in a vertical tank and the liquid circulated through the unit, new solid being introduced either continuously or in small slugs as the material in the reactor is dissolved in the reaction mass or removed from the bottom of the unit. If the solid is of such low density that it tends to float, the liquid is normally passed downward through the bed. Otherwise there is no restriction to the direction in which the liquid may be passed.

The fluidized techniques for solids in a liquid are also being applied. They are almost identical with those used for the gas-solid system.

The necessity for elevated temperatures and the simultaneous requirement of increased pressures ordinarily indicate a batch-type reaction. In this case a gas-tight pressure vessel is usually filled with the solid and the liquid added to the unit until it is filled. Circulation may be secured by removing the liquid from the bottom or top and reintroducing it at the opposite end of the reaction vessel. Heating or cooling, if required, can be achieved easily by introducing heat exchangers in the circulation line, usually just after the liquid has left the circulating pump. The natural direction for the circulation of liquid would be downward in the reactor if heat is needed, and the reverse if the liquid is

cooled as it passes the exchanger. However, the liquid is frequently introduced at the bottom of the reactor even when heat is supplied to it, for its lifting action as it flows upward through the bed of solid material tends to agitate the solid and keep it from settling into a compact mass in the reactor.

Rotating reaction vessels, once widely used for the reaction of liquids with solids, have been almost entirely replaced in newer construction by a stationary vessel provided with outside liquid circulation.

Reactions of a Gas and a Liquid with a Solid. Whenever a gas, liquid, and solid are associated in a reaction mass, the solid, if in a state coarser than that which will form a slurry or paste with the liquid, becomes the dominant factor in the selection of the proper reaction vessel. Techniques differ very little from those used for a liquid-solid or a gas-solid system.

Reaction of a Solid with a Solid. Very few solids will react with one another at room temperature even though they may be quite reactive in solution. Those which do react often require ignition by a spark, flame or impact. Frequently, however, the reaction, once initiated, will propagate itself by internal development of heat or shock. Examples are the familiar explosives. The major problem in handling these materials is to keep them from receiving the initial detonation which will cause premature reaction.

For the relatively nonreactive solids the problem becomes the opposite—that of promoting the reaction. Solid materials, even if finely ground and thoroughly blended, even those having a strong tendency to react, may remain in contact for years without any reaction taking place. Therefore, many reaction masses consisting of solid materials must be heated to complete or incipient fusion so that they become surface-active and will react with appreciable speed. Others require large amounts of heat to sustain the reactions. The problem, therefore, becomes one of supplying heat, or of maintaining a high temperature, or both. This is doubly difficult in many cases because of the difficulty of conducting heat into a solid lump of many substances, and of transferring heat from a reactor wall to a solid mass within the reactor. It is often desirable to grind the materials to be reacted

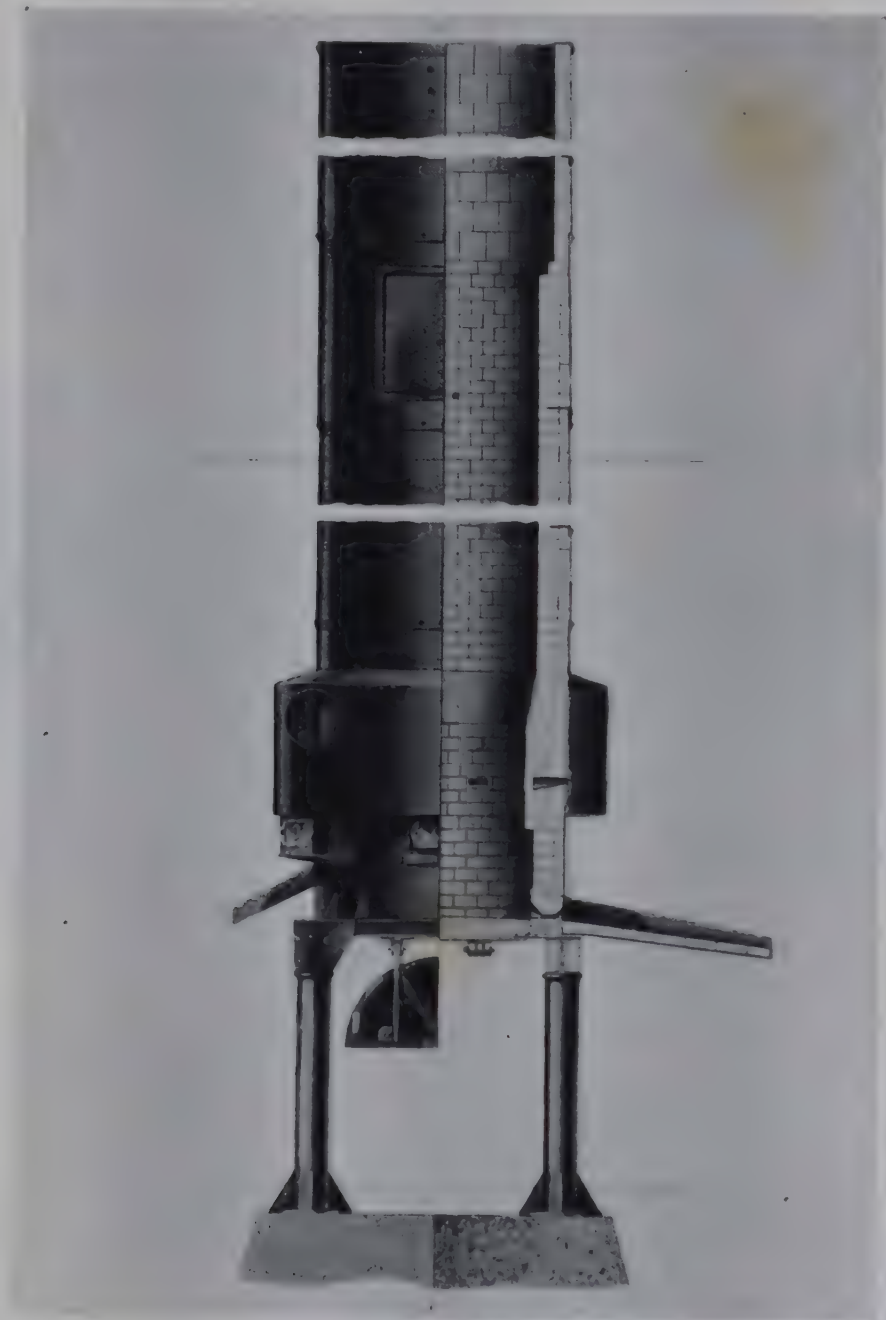
in order to improve the heat-transfer characteristics, and hence the reaction speed. Unfortunately, some types of reactions do not permit this step.

Reactors for solids are usually designed to permit solids to be brought to the reaction temperature and held at that temperature until the reaction is complete. For those few solid reactions in which temperature control is not necessary, any of the several solid-solid mixers becomes a reaction vessel as well as a mixer.

Continuous Reaction. Most of the reactors in which solids are reacted with solids do not require the application of pressure. Hence in those cases where the reaction temperature can be reached by the circulation of hot gases, or by the admixture of solid combustibles with the reaction mass which, in burning, produces heat for the reaction, or where the necessary temperature level is such that heat radiating from heated walls will be adequate, the reaction vessel can be made continuous.

High-temperature reactors for solids are usually known as kilns or roasters; they may be either continuous or intermittent in action. There are a number of styles of continuous kilns. The *vertical kiln* consists of a vertical, stoutly constructed cylinder, lined with heat-resistant firebrick. Heat generated in an outside stove and carried through the kiln with the products of the combustion is one method of heating. The favored method, however, is to mix low-ash coal or coke with the charge and to generate heat internally by introducing heated air into the base of the kiln. Solids plus fuel are introduced continuously at the top of the kiln, and are removed through a grate in the bottom or by being drained away as a molten mass. The vertical kiln requires a mechanically strong, lumpy solid for the best results. In contrast, the *rotary kiln* is particularly adapted to handling finely divided solids, although it will take any size up to coarse gravel. This unit is the largest moving reactor in chemical industry, being made in sizes up to 12 to 15 feet in diameter and as much as 300 feet long. It is a heavy, cylindrical steel casing, lined on the inside with several courses of heat-resistant brick, and arranged to turn slowly. The kiln is always mounted on a slight slant so that as it turns, the solids are mixed, tumbled into contact with the hot gases passing through the kiln, and moved

slowly from the upper (feed) end to the lower (discharge) end. The kiln is heated by the combustion of gas, oil, or powdered coal; the flames from the combustion often extend 40 to 100



(Harbison-Walker Refractories Co.)

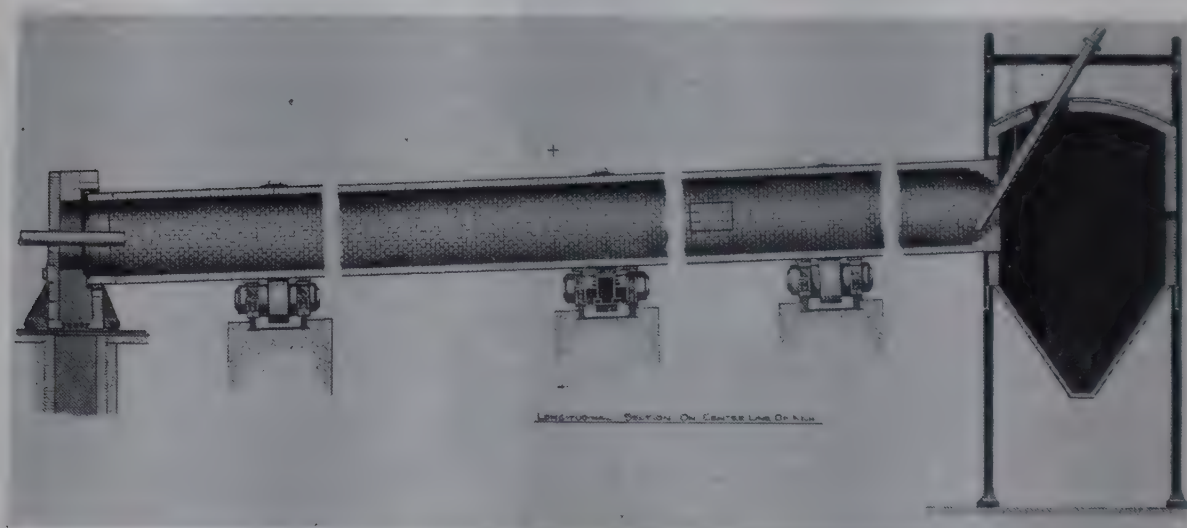
Figure 75. Vertical Kiln (Sectionalized view).

feet into the kiln. While there is no particular necessity for it, the flow of material in the kiln is usually toward the burner.

Tunnel kilns are designed to heat materials without subjecting them to the rough treatment which they are given in the vertical or rotary kilns. These are frequently used for firing pottery and

porcelain, and for heat-treating glass or metal parts. The kiln, as its name suggests, is tunnel-like in shape. The material is loaded on cars or a moving belt to be carried through the kiln. Heat may be supplied by gas burners located in the walls, or by outside stoves. It may also be heated by electrically heated walls.

If the final product is removed as a liquid, or even sometimes as a solid, and the reactants are solid or partly solid and partly liquid, a *horizontal kiln* can occasionally be used. An example of this is the continuous glass furnace, in which the solid sand, soda ash, broken glass and other materials are mixed together at one



(Harbison-Walker Refractories Co.)

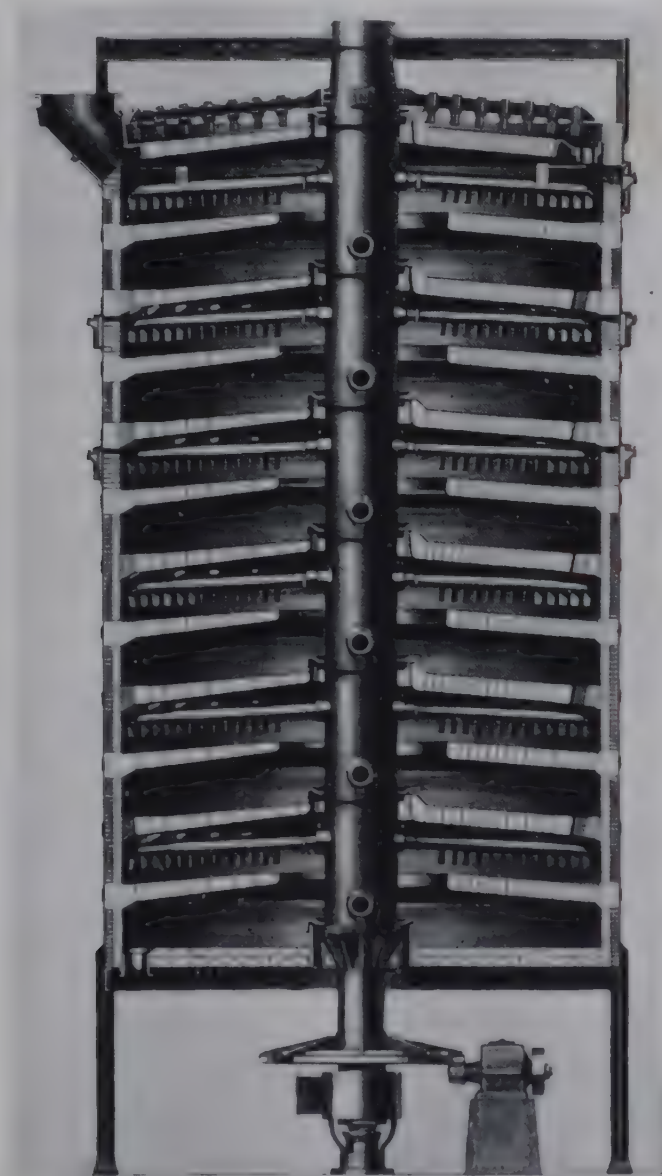
Figure 76. Rotary Cement Kiln (Longitudinal section).

end, and the liquid glass withdrawn at the other. The contents are heated by passing hot gases over the surface of the material in the kiln. Much of the heat is transferred from the gas or flame to the arched roof, which is heated to glowing; the heat is then transmitted downward on the contents by radiation. This is the reverberatory principle of furnace operation.

The *electric-resistance furnace*, one of the very high temperature producers, can be operated as a semi-continuous unit. In this device the electrodes are lowered vertically into the resistance mass. Products are withdrawn from time to time from the bottom of the furnace and gaseous products may be evolved continuously from the surface. Solid reactants are mixed and added in small batches and the electrodes adjusted after each addition, if necessary, to give the desired current flow. If the products are

not liquid or gaseous the electric furnace cannot be operated as a continuous unit.

Where somewhat lower temperatures than are obtained in the various kilns are necessary for reaction, a type of unit known as



(Harbison-Walker Refractories Co.)

Figure 77. Multiple-Hearth Roasting Furnace. Herreshoff.

the *rotary hearth*, or shelf-type roaster can be used. The unit most used in this operation is the Herreshoff roaster. This consists of a series of flat circular hearths inside a vertical fire-brick-lined steel shell. On each hearth there is a slowly moving set of plows attached to arms radiating outward from a central shaft. The material on one hearth is slowly turned by the plows and moved

toward the edge of the hearth. As it reaches the edge it is dropped to the hearth immediately below where it is moved toward the other edge. Hot gases are conducted over the surface of the material on the hearths.

Many devices for reacting solids, similar to the roaster or kiln, have been introduced from time to time, but for the most part these are not superior to existing types.

Batch Reaction. Many reactions of solid materials are carried out as batch operations. The batchwise operation, while more expensive on a large scale than a continuous operation, does offer some advantages. It is somewhat more adaptable to small scale requirements. It almost always offers better control of reaction variables. If the products as well as the raw materials are solids, and if, simultaneously, the high temperature of the electric arc or resistance furnace is required, the batch method may be the only one which can be used. Batch operation is normally more satisfactory if it is essential that the solids be kept completely separated from the heat source.

Some of the more widely applied batch operations for reacting solid materials are roasting of ores; preparation of certain dry colors in which the progress of the operation must be carefully observed; open hearth operations for the adjustment of carbon content and addition of certain alloying substances to steel, an operation which is slow and must be very carefully checked as it progresses; production of electric furnace steel for steel castings; and production of certain solids, such as calcium carbide, silicon carbide, "Alundum" and others which require the high temperatures of the electric furnace for their production. The several types of coal retorts are also widely used batch-type reactors. Stationary brick kilns are a familiar sight.

The *open hearth* for steel is a reverberatory furnace in which solid materials are added but are melted and reacted in the molten stage. The furnace is charged in the horizontal position, and is tilted to discharge the molten steel. Reverberatory furnaces are also used for other metallurgical and smelting operations.

The *electric steel furnace*, like the open hearth, is charged with solid material which is quickly melted at the temperature of the electric arc which is formed within it. Since in this furnace the

heat is introduced into the charge without using a heated gas stream, contamination of the liquid steel can be avoided. More accurate control of heat input can be obtained, as well as higher temperatures, if desired. This furnace, too, is ordinarily tipped to discharge the molten batch.

Where reaction of solids produces a solid product and requires the high temperature of the *electric resistance core furnace* a batch-type reaction is nearly always indicated. In this type of reaction the mixed charge of reactants is built up around a core of granular carbon in the ends of which are inserted solid carbon electrodes. The reaction mass is supported by a loose brick wall held in place by movable iron sections. Unreacted charge actually forms the walls for the reaction mass. When the reaction is complete, the power is shut off, the mass is allowed to cool, and then the entire furnace is torn down to remove the reaction products. This is probably the ultimate in batch reactions.

The various coal distillation retorts are widely used batch-type solid reactors. The most popular retort in use at the present time is the *vertical retort* which is a vessel built of heat-resistant ceramic shapes, some 14 to 20 inches wide, 20 to 30 feet or more long, and as much as 20 feet high. The coal is charged to the inside of the retort, and the inlet and outlet doors closed to provide gas-tight seals. Heat, conducted to the charge through the walls, causes decomposition of the coal to form various liquid and gaseous products, and solid coke. The gases and volatilized liquids are led away from the retort as the reaction proceeds, and the coke is simply pushed out the end of the retort by a mechanical ram when the reaction has been completed.

Electrolytic Reactions

The techniques for carrying out the reactions produced by the passage of an electric current through solutions of various substances (electrolysis) are unique, and hence do not fit into any of the previous classifications. Electrolysis is most frequently applied to produce elements from their salts, but is also used to produce other chemical substances. However, with one exception (caustic soda), these account for only a small portion of the electric current used for these purposes. Electrolysis for the production

of chemical elements and compounds may be conducted in a water solution of a salt of the substances, in nonaqueous solutions of certain salts, and in some cases from the fused dry salts themselves. Water solution and fused salts are the two most important electrolytes.

In the purification of metals, a plate of the impure metal is suspended in a solution of a salt of the metal. This plate is the anode of the electrolytic cell. A thin sheet of pure metal or another metal from which the electrodeposited pure metal can be readily stripped becomes the cathode. The anode goes into solution as the metal is plated out of the solution on the cathode. Impurities fall to the bottom of the cell and are withdrawn as a sludge.

Several types of cells are used for electrolysis of sodium chloride solution for the preparation of chlorine and caustic soda. The major problem is to keep the hydrogen, from the reaction of sodium and water, separated from the chlorine. The use of diaphragms to separate the gases mechanically, or mercury in which the sodium is dissolved before it can react are two methods of approach.

The production of magnesium from fused magnesium chloride is an example of the electrolysis of a fused salt. The reaction vessel in this process consists of a ceramic-lined steel cell. The cathodes are steel bars and the anodes are graphite. A shield around the anodes collects the chlorine which is produced. The baths are kept at temperatures of about 1,250°F. by oil- or gas-fired furnaces under the cells. As magnesium is produced it rises to the surface and is withdrawn.

SECTION V

THE SEPARATION AND
PURIFICATION OF MATERIALS

14 : SEPARATION OF A SOLID FROM A SOLID

Techniques for Separating Solids from Solids

- By difference in appearance or color
- By difference in size
- By difference in weight and density
- By difference in hardness
- By difference in smoothness
- By difference in shape
- By difference in surface adsorptive properties
- By difference in melting points
- By difference in vapor pressures
- By difference in response toward heat
- By difference in solubility
- By difference in magnetic properties
- By difference in electrostatic properties
- By difference in electrodeposition conditions
- By difference in chemical properties

A reaction seldom yields a single product without the presence of contaminating by-products or residues of unreacted raw materials; equally seldom can a mixture of reaction products, by-products and raw materials be used without purification. Also, it is often necessary to upgrade the quality of a raw material before it can be used effectively in a chemical process. The techniques involved in such an upgrading of raw material are the same as those used in purifying the products of a reaction.

The separation of two or more solid substances from one another is dependent upon differences in the physical or chemical properties of the materials. In those cases where there are insufficient differences in properties to form a basis for separation, differences can sometimes be induced by the imposition of certain conditions, such as high or low temperatures, pressure, electrical or magnetic fields, or chemical action.

While chemical action is effective both as a direct means for separation of materials and as a means for augmenting differences in properties, it should normally be used only as a last resort. Chemical reaction is usually more expensive than the purely physical methods which may be employed for separation.

The techniques for separating one solid from another are usually well defined by the differences in physical properties. Some of the more important are differences in:

1. Color or appearance
2. Size
3. Density and weight
4. Hardness
5. Smoothness of surface
6. Shape
7. Surface adsorptive properties
8. Melting point
9. Vapor pressure
10. Response toward heat
11. Solubility
12. Electrostatic properties
13. Magnetic properties
14. Electrodeposition conditions.

Among the important chemical properties which can sometimes be used for separation are those relating to the reaction of the materials with air, with a cheap alkali such as lime, or an inexpensive acid such as sulfuric acid. The physical properties usually altered by chemical action are the solubility or the physical state.

General factors which may apply to the selection of a separation technique are:

1. The amount of material to be handled (total and peak rates)
2. The relative proportions of the materials present
3. The purity required
4. The necessity for saving materials other than the primary product
5. Recovery of by-products

TECHNIQUES FOR SEPARATING SOLIDS FROM SOLIDS

The techniques and equipment available for the separation of solids are most easily classified according to the differences in

properties of the materials involved. There are a few instances in which similar techniques and equipment may be equally applicable to the separation of material in more than one classification. However, this is not particularly important in the overall problem except to give additional versatility to equipment.

Separation by Difference in Appearance or Color

Practically all commercial products have to meet certain requirements as to appearance; hence considerable effort is made, consciously or unconsciously, to separate acceptable from unacceptable items by appearance alone. Some industries still practice visual inspection by trained observers, who either physically separate the materials or operate machinery which does. It is the only practical solution to certain problems of separation, particularly many of those required in the preparation of foods. There has been much effort to replace visual inspection by use of the photocell, or by some mechanical device. These have met with varying success. Methods of visual inspection, such as the color-matching of dyes and paints, are giving way to the electronic color analyzer.

Separation by Difference in Size

Separation by Differences in a Single Dimension. There are some substances, notably textile threads and paper, for which accurate thickness of the material is critical. Devices are available for either hand or automatic gaging of thickness of thread and sheet material. The shop caliper is too slow and tedious for inspection, except as a means for checking the more convenient spring-loaded thickness gages. Automatic and continuous thickness gages are made by replacing the anvils of the hand gage by two rolls between which the material to be gaged can be led. These gages are often fitted with electrical contacts and relays for sounding alarms or for making automatic adjustment of feed devices if the thickness goes above or below a specified value.

Separation by Differences in Cross-section. The separation of solid materials by differences in the dimension of the smallest cross-section of a particle is a widely used and extremely important operation. The technique involved is that of screening;

it has been described in the chapter dealing with size classification. When solids are intimately associated in the dry state and resist separation by screening, they can sometimes be disassociated by thorough agitation in water or by washing under water sprays, and can then be separated by screening, or by one of the methods mentioned for separating solid particles of different volumes.

Separation by Differences in Volume. There are several techniques available for the separation of materials by differences in volume. Two general principles are involved. One is that the smaller a particle, the greater the surface area per unit of weight, and hence the more it will be affected by the medium in which it may be held. A slightly different principle is that a large particle will be less affected by a surface over which it is rolled than will a small one of the same density. The techniques and equipment employing these principles—the air and water classifiers, the thickeners, decanters, cyclone separators, Wilfley tables and screenless sizers—have all been previously discussed. Several of them are extremely useful in the separation of materials on the basis of differences in size.

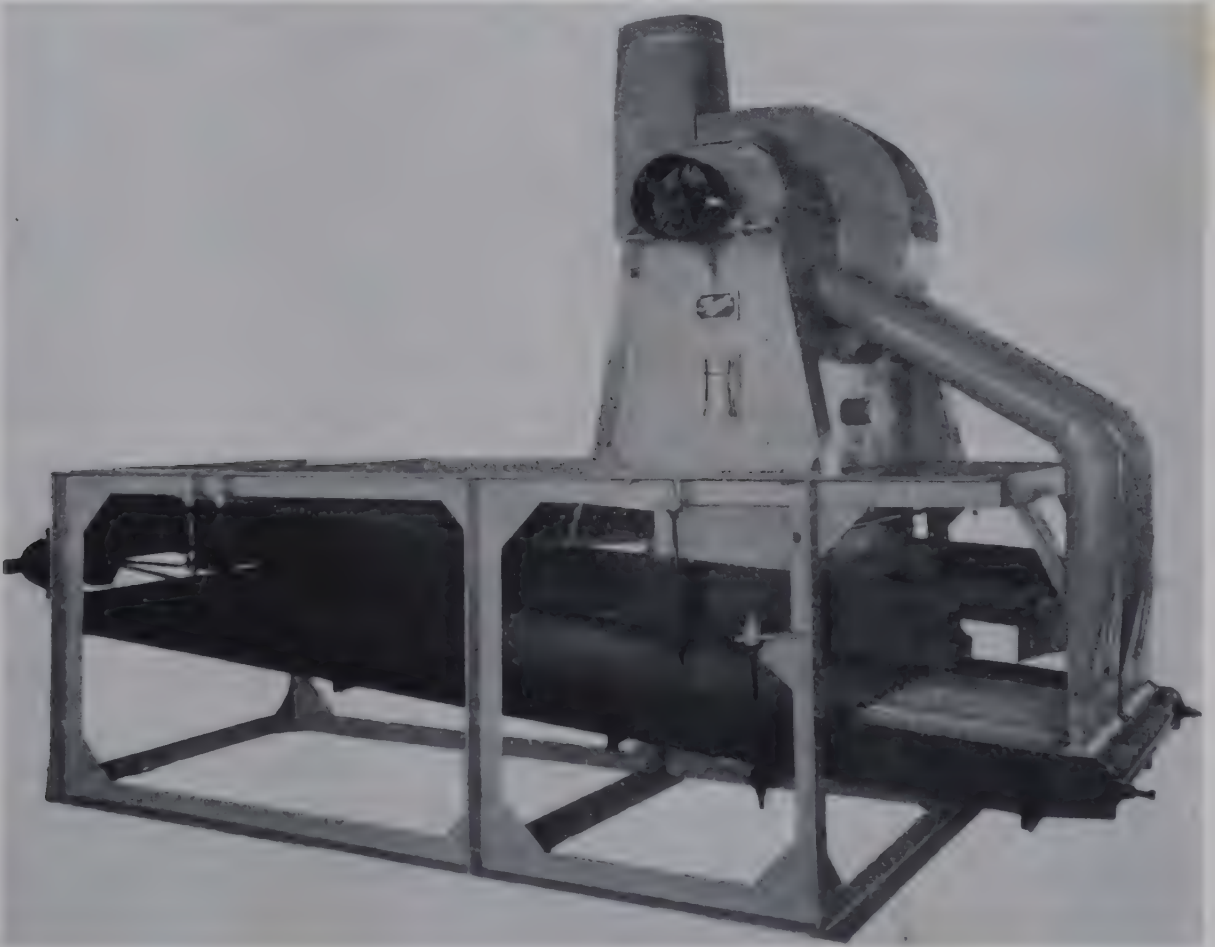
Separation by Difference in Weight and Density

Separation by Weight. The weights of individual items, such as a can of paint or an artillery shell, may sometimes be used as a yardstick for judging acceptability of a product. This separation may be effected manually by weighing each item, under-and-over scales being particularly useful. Automatic balances which will eject any units too light or too heavy are widely used.

Separation by Differences in Density. The principles on which the techniques for separating solids by density are based are similar to those used in the various classifications of materials by differences in volume. One of these is the fact that a particle weighing more per unit of surface area will be less affected by external conditions, such as turbulence and flow of the medium in which it is held, than will the particle of lighter weight. The second principle is that if two solid particles of similar size and shape but of different weight are rolled down a roughened slope not steep enough to impart a high gravitational velocity, the

heavy particle will tend to cling more closely to the surface and therefore will be more retarded in its movement by irregularities in the surface.

One of the most widely used techniques of separation on this basis is that of dropping a material into or through a moving stream of air. This method has been used for centuries for separating grain from chaff and straw.



(The Bauer Bros. Co.)

Figure 78. Pneumatic Separator.

Another method of separating materials by differences in density is to pass them in a thin layer under a vacuum pickup. If the material is agitated slightly as it passes under the intake nozzle, and if the air flow is carefully adjusted, the lighter materials will be pulled off and out of the mass, and the heavier particles will remain behind.

Separation of solids of different weights may sometimes be accomplished in an elongated settling chamber by reducing the

velocity of an air stream and allowing the solid material suspended in the stream to settle into bins along the bottom of the chambers.

Separation by projection operates on this same principle. The heavier particles when discharged rapidly in a horizontal direction will travel farther from the projecting device than will the lighter particles of the same diameter.

There are also several settling techniques for segregating the heavier particles in the bottom of a mass of finely divided material by partially suspending the entire mass in water or other liquids. This is the principle of the *mineral jig*, which is a modern power-driven version of a much older hand-driven machine used in the early gold-mining days. This device consists of two compartments. The mineral is placed in one compartment which is filled almost full of water; the second compartment, which is closed, is arranged to transmit pulsating agitation to the liquid in the mineral section. This raises and lowers the mineral and allows the heavy particles to work through the mass and collect on the bottom.

The *riffler* is another form of settling chamber in which heavy particles are separated from lighter particles in a stream of water. These are long troughs having a series of shallow basins formed along the bottom by low baffle boards.

Concentrating tables, usually used wet, utilize the combined effect of the retarding action of a roughened surface on a heavier particle, and the tendency for a heavier material to sink to the bottom of an agitated mass. Their use for mineral concentrating is widespread. They consist of an elongated tilted platform, across which the particles are moved by an eccentric motion of the platform.

The major precaution in separating solid materials by differences in density is to feed only materials of approximately the same dimension. Otherwise, with any of the air or liquid classifiers, the large particles of the lower-density material will sink at the same speed as the smaller particles of high-density material, and hence will be mixed with them.

The "sink and float" process, widely used in the metallurgical industry, is based upon the use of a suspension of finely divided

solids. The density of this mud is so adjusted that it will permit the separation of two mineral substances of lighter and heavier densities than the mud. After the separation is effected, the fine solids are removed from the separated particles, slurried and returned to the process.

Separation by Difference in Hardness

Certain difficultly separable materials, if they have different hardnesses, can sometimes be separated by squeezing, pushing, or pulling the soft portion through an aperture too small for the harder portion to pass. This method of separation does not often have application in the strictly chemical industries, but is important because it forms the basis for operation of one of the most important machines of all time—the cotton gin.

Separation by Difference in Smoothness

At least two techniques useful in the separation of materials are made possible by differences in the smoothness of the surface. The first of these employs the principle of interstitial action. For example, in factories processing oats, hulled oats are separated from unhulled oats and hulls by shaking the mass on an inclined table. The hulled oats are slippery and will settle to the bottom, where they can be withdrawn from the mixture.

An altogether different mode of operation is used to separate slate from coal. This method, especially useful in cleaning anthracite, consists of dropping the lump material on a traveling continuous belt which is tilted as it passes under the feed. The coal, which has much less surface friction than the slate, drops over the lower side of the belt almost immediately. The rougher slate clings to the belt and is carried to the end of the belt travel, where it is discharged.

Separation by Difference in Shape

Techniques involved in the separation of solid materials by differences in shape have little interest in the chemical industries. However, the possibility should be mentioned in view of the ease with which they might be applied to some particular situation. A novel application is the method of separating spherical shot

from those not quite spherical. The shot are rolled down an incline. The perfectly round shot will roll faster, gain more momentum, and be projected farther from the end of the incline than will oval-shaped shot, which tend to wobble from a true course as they pass down the surface.

Separation by Difference in Surface-adsorptive Properties

One of the most important industrial techniques for the separation of solid materials takes advantage of the fact that certain substances have an affinity for oils, greases, and gases, or have a depressive effect, in themselves, on the surface tension of water. This is the technique of flotation. Early flotation operations were limited to the separation of certain sulfide ores from rock gangue with which they are always associated. With the further study of surface properties, and of various flotation agents, the list of materials which can be separated by this technique has become very large and is increasing continuously.

Several methods based on this principle are in use. The only one having any particular significance is known as froth flotation. The surface-active material to be separated is caused to rise to the top of the liquid in a tank in a froth which is formed by blowing air into the bottom of the tank. The equipment for this operation consists of a tank which will hold the material to be floated and the liquid in which it is mixed, a means for introducing air near the bottom of the tank, and a scoop or paddle for skimming off the froth as it is formed.

A few materials have water-repellent properties, and hence if finely ground and placed in water will immediately rise to the surface with the froth. Most materials do not have these properties, but many have been found to have surface properties which will cause the adherence of thin films of oil, tar, creosote, and many other materials. When coated, these can be separated by flotation.

Several classes of chemical materials are used in flotation techniques, and are described below. The number of chemicals in each class is growing rapidly.

Collectors are those agents which have a high affinity for the material to be floated and will deposit in a very thin, possibly

monomolecular, film over the surface of the active material. Materials such as alpha-naphthalene, thiocarbonates, fatty acids, soaps, kerosene, and others are used as collectors for a variety of solids.

Frothers are chemicals such as pine oil, cresylic acid, and other chemicals which have a high affinity for air and create a heavy froth as air is distributed into the slurry.

Depressors are added to prevent the flotation of one material and hence permit the separation of two materials which would otherwise be floated together. For example, lime will depress pyrites, and chromate salts will keep galena from floating. There are many other examples.

Deflocculating agents are used to disperse the slime of the froth which is skimmed off; hence they serve to clean floated minerals. Various detergents have been found useful for this purpose.

Other materials are used for controlling the acid or base concentration, for activating certain minerals so they will be properly floated by the collectors and frothers, and for improving the water solubility of certain agents.

Separation by Means of Difference in Melting Points

A very effective method for the separation of certain solids is based on their difference in melting points. Single components out of some solid systems are quite easily liquefiable and can be readily drained away from the solid residues. The major difficulty in most such separations is associated with the fairly difficult task of conducting heat evenly into the mass so material will be melted out. There is also usually a considerable tendency for the liquid to be held mechanically in the solid residue.

Separation by Difference in Vapor Pressures

A few solids exhibit considerable vapor pressure, even below their melting points, and hence can be converted from the solid to the vapor state and back without going through the liquid state. This phenomenon is known as sublimation. It forms the basis for several commercial separation techniques.

Sublimation is usually avoided as a method of separation if

other methods will suffice. The difficulty of getting heat to the material without overheating and consequent damage, particularly to organic substances, plus the difficulty of condensing a vapor to a solid, discourages the use of these techniques, except where there is no other satisfactory solution to the problems of separation.

Separation by Difference in Response toward Heat

Some minerals disintegrate when heated (decrepitate). These can be separated from rock by heating the mass and screening it. Heating is usually accomplished in a unit like the Herreshoff roaster, or a rotary kiln, where the agitation of the mass tends to assist in the disintegration of the material as it is heated.

Separation by Difference in Solubility

If two substances associated in the solid state have substantial differences of solubility in water or in other solvents or solutions, they can be separated easily and cheaply. The only difficulty lies in the fact that it is quite often the desired product that is dissolved, and the separation of that material by solution normally requires an additional step to remove it from the solvent.

The solution of one solid out of a mixture of solids is an operation known as leaching. There are two techniques for leaching. In one of these, leaching by percolation, the solid is left in the massive condition; the solvent is passed over this solid, and the resultant solution is drained away by gravity. In carrying out the other technique, the solid is ground to reasonably fine particles which are agitated with the solvent. The resultant insoluble sludge must be separated from the solution by one of the several separation techniques available for the separation of solids from liquids.

The equipment requirements for percolation leaching are simple, consisting of merely a tank or tower in which the solid may be placed, and a means for passing the solvent through the solid mass. The technique is not easily made a continuous operation, but it can be made semi-continuous by arranging several dissolvers in a battery.

Leaching by agitation of the solid and liquid can be carried out by at least two different techniques. The first keeps the solid particles and solution in motion relative to each other; the second involves a continuous suspension of the solid particles in the liquid system.

Any of the several classifiers described in the chapter dealing with the separation of a solid from a liquid can be used for transporting the solid through a liquid system, in which leaching can take place.

The second technique involves an actual agitation of the solid-liquid mass, the mixing being mild or very turbulent depending on the ease with which the particles settle in the leaching tank. A highly satisfactory mixing and leaching operation can sometimes be carried out by wet-grinding the solid in a ball or rod mill.

The percolation technique has several important advantages over agitation leaching. It is somewhat better adapted to materials in the massive form; it is easily operated as an excellent countercurrent system, which allows high solution concentration and excellent removal of soluble material from the solid mass; it can be easily conducted under pressure if necessary; and it does not agitate or tend to break up the solid particles. However, the percolation technique is not easily adaptable to continuous operation, and it does not handle satisfactorily finely-divided material or any other material which would tend to pack in the dissolving tank.

Leaching by agitation, even where the classifier is used, usually requires considerable additional equipment for separating the solution and the undissolved solid. This procedure may not be difficult; if it is, it may discourage this approach to the problem of separation.

In the discussion relating to the separation of solids by dissolving one and leaving the other, it has been assumed that their solubilities are quite different. This represents the ideal situation. In many cases, however, both solids may be soluble or insoluble in a liquid; but it still may be possible to separate them more or less completely through leaching by resorting to selective treatment of the material. One of the most obvious methods of varying the leaching technique is to substitute another solvent for the

first choice, usually water, if it is found to be unsatisfactory. Many organic materials, insoluble in water, show varying degrees of solubility in organic solvents. When these materials are in a mixture, the problem of separating them can often be solved by the selection of an organic compound having the proper solvent characteristics.

The major drawback in using some solvents is that they may be too expensive to be lost in any appreciable amounts. Therefore, in addition to the operation required for separating the solvent from the dissolved portion, an operation must be introduced to recover the solvent from the undissolved solid. Another point in connection with the use of organic solvents is that many of them are quite volatile and must be used only in vapor-tight equipment, whereas water can be used as a solvent in almost any kind of open tank.

Another type of solvent action can be obtained by using a solution of a salt or chemical substance as a solvent in the process. The presence of certain ions in solution will often suppress the solubility of one substance while others are not particularly affected.

The suppression of solubility also has an application in a completely different technique for the separation of solid materials. In carrying out this procedure, both solids are put into solution, and one of them is precipitated by adding a material which reduces its solubility in the solution.

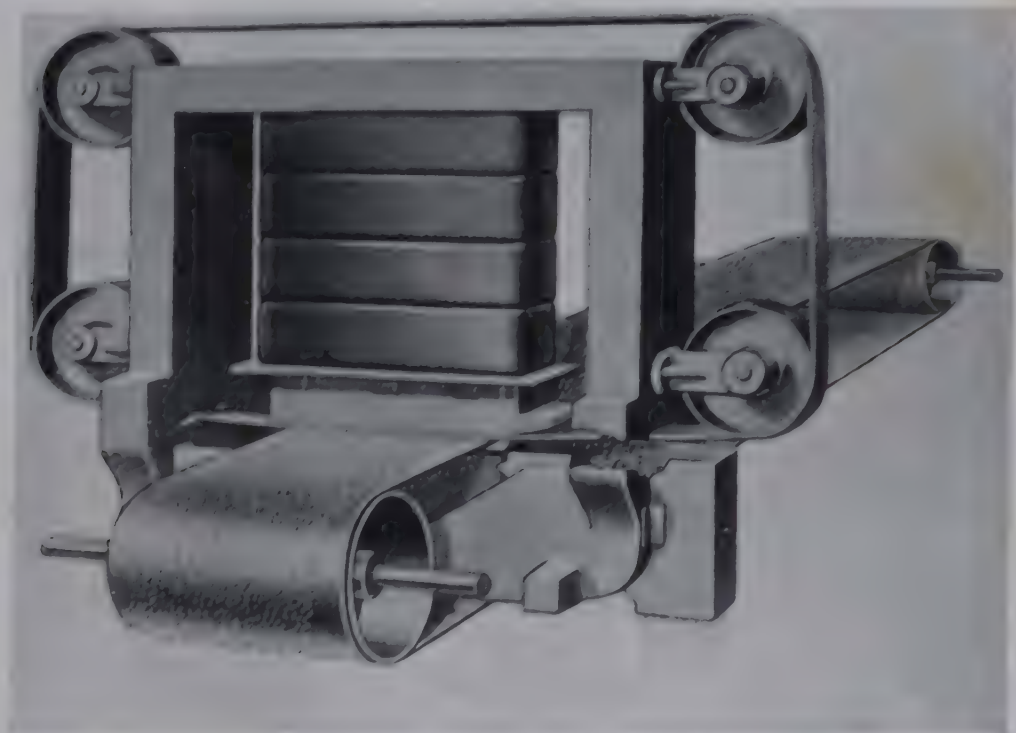
Changing the temperature of the solvent may serve to precipitate one solid out of a mixture in a solution, or selectively dissolve one material out of a mixture completely soluble at ordinary temperatures. This technique must be carefully controlled to give desired results.

The possibility of diffusion of a soluble molecule of small size through a membrane, leaving behind another soluble molecule of larger diameter, is another characteristic of some systems which offers a means for selective separation of two substances, both of which may be soluble at the conditions under which the leaching operation is conducted.

One technique to effect a selective removal of one soluble material from a mixture of soluble materials makes use of the

relative rates of solution, and controls the time of contact of the solvent with the solid mixture. This is usually difficult to accomplish successfully.

In general, the several leaching techniques are used widely and effectively for separating solid materials. They cannot, of course, be employed to separate many mixtures of solids, although



(Ding's Magnetic Separator Co.)

Figure 79. Magnetic Separator; cross belt type.

their field of application is being continuously broadened with the development of many new solvents.

Difficulties common to all the leaching techniques are that at least one of the several materials in the solid mixture leaves the process in solution, and that the residue is wet with the solvent.

Separation by Difference in Magnetic Properties

Certain ores and metals may have magnetic properties, while the material with which they are associated may be non-magnetic. When this situation exists, the magnetic material can be easily and cheaply separated from the non-magnetic by passing the two between the poles of a magnet where the magnetic material will be lifted out of the mass. The complete separation is of course,

impossible, if the two materials as, for example, in an ore, are associated in the same particle. However, if the ore is finely ground there is a definite possibility for upgrading by magnetic separation. For separating scrap iron from other metals or for separating tramp iron from rock or other materials the method is invaluable.

It is of interest that some materials not naturally magnetic or very weakly so, can be treated to make them more strongly magnetic. Pyrite, for example, may be converted to pyrotite, a slightly magnetic material, by a controlled oxidizing roast.

There are several types of equipment available for making this separation. All have some type of magnet, a means of bringing material into the magnetic field, and provision for removing the separated material.

It is frequently desirable to make a magnetic separation of materials in a water slurry. As a matter of fact, it is far better to handle very finely divided materials suspended in a liquid, for not only is the separation more likely to be complete, but also the difficulties from dust can be avoided. This operation is entirely possible and several wet magnetic separators are marketed.

Separation by Difference in Electrostatic Properties

Some materials (nonconductors) in granular form will receive an electrostatic surface charge which they will hold for a short time. If these materials are promptly transferred into an electrostatic field, the charged grains, depending on the sign of the charge, are either attracted or repelled by a charged electrode.

Separation by Difference in Electrodeposition Conditions

Several metals such as copper, lead, zinc, and many others may acquire small amounts of alloying metals as they are smelted. These are derived from the impurities in the ores.

The problem of the separation of these metals to produce pure base metals, and to recover metallic values from the impurities, has been solved by electroplating the desired metal out of a bath containing that metal in solution. The crude metal is cast into sheets which are used as anodes in an electrolytic cell. The purified metal is plated out on pure metal cathodes, or on cathodes made

of aluminum or other materials from which the electrodeposited metal can be stripped.

By controlling temperature, concentration of the active compound in solution, current densities, voltages, and the acidity or alkalinity of the electrolyte, the desired metal can be made to plate out of solution, to be replaced by metal which goes into solution from the anode. The impurities remain as sponge-like materials on the face of the anode, or drop to the bottom of the cell in the form of a mud which is periodically drained from the cell and treated for the recovery of the metals it contains.

The electrodeposition of metals to effect their purification has solved many separation problems which would otherwise have been very difficult and expensive. The annual production of electrolytically refined metals extends into the millions of tons.

Separation by Difference in Chemical Properties

When it has been determined that a mixture of two solid materials cannot be separated by physical means, then the chemical properties should be examined to see if there are any which can be made the basis of a separation. There are some notable exceptions to this rule where chemical methods are used for separations when physical methods might also be effective, but for the most part, chemical methods of separation are used as a last resort.

Usually, although not always, chemical methods of separation can be used only as an adjunct to physical separations, and not only must the materials themselves be separated, but the chemicals which have been used in the separation must also be removed. Further, the chemical nature of at least one of the materials must have been changed, and if it is necessary to regenerate the material to its original chemical form, additional problems may be introduced. Finally, the cost of the chemicals must always be taken into consideration. While the quantity used may not be large, there are only a few which are so cheap and easily procured that their cost is not many times that of power and other items used in connection with purely mechanical or electrical separations.

While it is perfectly possible to change any of the several properties of solid materials upon which techniques for separation are

based, the two properties most frequently altered by chemical action are the state and the solubility.

The number of chemical changes of properties effected for the purpose of making a separation is very large. An excellent illustration of the change of state by chemical action and concurrent separation of a solid material from a mixture, is that of the removal of carbon from steel in the Bessemer converter. Here the molten steel is blown with air, thus oxidizing the carbon, which is discharged as gaseous carbon monoxide.

An example of the change in solubility by chemical treatment as a means for the separation of solid materials is in the preparation of chemical pulp from wood. In this case the wood, composed of cellulose (the chemical pulp portion) and lignin is treated with various chemical solutions. The lignin is rendered soluble, and that portion not dissolved out in the cooking liquor itself is washed out in subsequent leaching operations.

15 : SEPARATION OF A LIQUID FROM A SOLID

Techniques for the Separation of Liquids from Solids

Techniques for partial removal of liquid

- By gravitational force

- By centrifugal force

- By application of vacuum

- By application of a mechanical force

- By the action of a solvent

- By displacement

Techniques for complete removal of liquid

- By vaporization

Special Considerations in the Separation of Liquids from Solids

There are many reasons why the separation of a liquid from a solid is highly important. Outstanding among them is the need for reducing weight of a solid material in order to lower shipping charges. It is frequently important to reduce moisture content so there is less likelihood of spoilage of the material when in storage. Water removal is often desirable, at considerable expense, even when water is to be reintroduced into the solid mass before it is used. Many other objectives, such as purification and solvent recovery, are also desirable.

To avoid any misunderstanding of the conditions under which the particular techniques described in this section are carried out, it should be stated that this separation is to be considered on the basis of removing a liquid from a mass which is essentially solid in character—which has the properties of a solid and can be handled like one, both initially and finally. Another chapter deals with the separation of liquid-solid mixtures which are, initially at least, in the liquid state, and can be treated as liquids.

Most of the properties and principles upon which techniques

for the separation are based are those relating to the liquid. For the most part, it must be considered that the solid is essentially nonvolatile, insoluble in the liquid portion of the mixture, and for all practical purposes at least, unaffected by the treatment to which it may be subjected for the removal of the liquid portion of the mixture.

In the selection of a technique for the separation of a liquid from a solid, consideration should be given to the following factors:

1. Properties of the liquid
 - a. Vapor pressure
 - b. Decomposition temperatures
 - c. Viscosity
 - d. Density
2. Properties of the solid
 - a. Decomposition temperatures
 - b. Solubility
 - c. State of subdivision
 - d. Fragility—necessity for careful handling
 - e. Surface adsorptive properties
 - f. Elasticity
3. Relationships between liquid and solid
 - a. Mechanically-held liquid
 - b. Liquid adsorbed on solid surfaces
4. Degree of removal required
5. Requirement for regenerating pure liquid or pure solid, or both
6. Cost of equipment
 - a. Initial
 - b. Maintenance
 - c. Operation
7. Availability of equipment

TECHNIQUES FOR SEPARATING LIQUIDS FROM SOLIDS

The methods by which the separation of a liquid and a solid may be effected can be classified in several ways. A satisfactory division into two groups can be made according to the degree of liquid removal to be accomplished. In the first group are those

techniques in which the liquid is only partially removed; in the second group are those in which the concentration of the original liquid is reduced to almost zero, or, in the case of water removal, to an "air-dry" condition. Many operations for the removal of liquids are conducted stepwise; one technique may be used first to reduce the liquid content, followed by a different one to remove the remainder of the liquid present.

Techniques for Partial Removal of Liquid

Any of the techniques described later in this chapter for the complete removal of a liquid can be used for partial removal of a liquid by not permitting them to be carried to completion; they are often so employed. However, several techniques cannot effectively carry the liquid concentration below certain levels. These are described in this section.

Removal of Liquid by Gravitational Force. In a number of liquid-solid mixtures the liquid is held very loosely on the surface or in the pores of the solid, and will migrate downward by gravity through the mass of material. While this is not usually to be recommended as an industrial method for liquid removal, the fact remains that, although inefficient, it may partially remove a nonviscous liquid from a solid mass with very little investment in equipment, and for some purposes it may be satisfactory. To carry out this technique, the material to be drained may be piled on grillwork floors where the adhering liquor can slowly drain away through the openings in the floor.

Removal of Liquid by Centrifugal Force. The techniques for removing liquid by centrifugal force are similar to the gravitational methods for draining the solid mass, except that the force applied for the extraction of the liquid may be made many times that of gravity. An excellent degree of separation can be obtained. The liquid can be quite viscous and yet be effectively removed from the solid mass. The machines available for this separation are the basket-type centrifuge, which is intermittent in operation, and the so-called "continuous centrifiner," a continuous centrifugal separator.

In spite of the fact that it is a batch-type unit, the *basket centrifuge* is the most important device of its kind for liquid-solid

separation. It is simple in design, and with proper care will give years of trouble-free service with minimum maintenance. It consists of a squat, perforated drum placed with its axis in a vertical position, and so arranged that it can be rotated at a high rate of speed. The basket is driven from either above or below. The solid-liquid mix is introduced as a slurry or semi-solid mass and quickly forms a layer against the sides of the rotating basket. The liquid drains through the solids and out through the perforations in the basket, and finally through drain outlets in the bottom of the casing. Plows scrape the residual solids off the walls of the basket. The solids are then discharged through ports in the bottom.

The major disadvantages of the centrifuge are that it is small in size and that, as it is batchwise in operation, a considerable amount of labor and a number of machines are required for any appreciable production. For this reason, constant effort has been directed toward developing a continuous centrifugal machine. Several fairly successful ones are now available. Most of these are satisfactory for free-moving solid particles mixed with a non-viscous liquid, but they will not operate successfully with sugar crystals, sewage sludges, and other sticky or slimy materials.

Removal of Liquid by Application of Vacuum. A method for increasing the driving force for dispelling the liquid from a solid mass is the application of a vacuum at the underside of the mass. This is the principle of the Büchner funnel and similar laboratory equipment. The same principle is used very effectively in the paper industry for dewatering paper stock. Virtually every paper machine is fitted with suction boxes or suction rolls which immediately follow the natural drainage sections of the moving wire screen on which the paper sheet is formed. Similar results are obtained in dewatering the solids caught and held on any of the vacuum filters.

Removal of Liquid by Application of a Mechanical Force. Many solid materials, even though finely divided, are sponge-like in character, and hold the liquid in pores either in or between the particles. The liquid can be expelled from these solids by mechanically compressing the solid mass. The application of pressure for the extraction of liquid from a solid has many uses in the chemical industry. There are several techniques for applying

this pressure, for bringing the solid mass into the pressure zone, and for removing the liquid and solid from it. The different pieces of equipment used in these various operations are all called presses, with a descriptive adjective to give a hint of their design or operation.

Intermittent Presses

In spite of the urgency to convert to continuous processes wherever possible, batch presses continue to be widely used in industrial chemical plants. The intermittent presses, in general, are somewhat more adaptable to varying loads than are the continuous presses, and will generally achieve better separation of liquid and solid. They require much more labor to operate, however. Intermittent presses are made in two general styles, the plate press and the curb press. Pressure is usually applied to either by means of a hydraulic cylinder or ram.

The *plate press* consists of a group of plates positioned within a set of guide posts. The plates are suspended from the top by steel links between the plates. When the press opens, the plates separate by the length of the links between them. The ram (piston) usually operates from the bottom upward, so that as the pressure is released the ram drops and the plates spread apart by gravity. There are several variations of the plate press, depending more or less on the method by which the solid is held between the pressure plates. A desirable feature of all plate presses is that they may be made with hollow plates which can be used for temperature control of the material while it is being pressed.

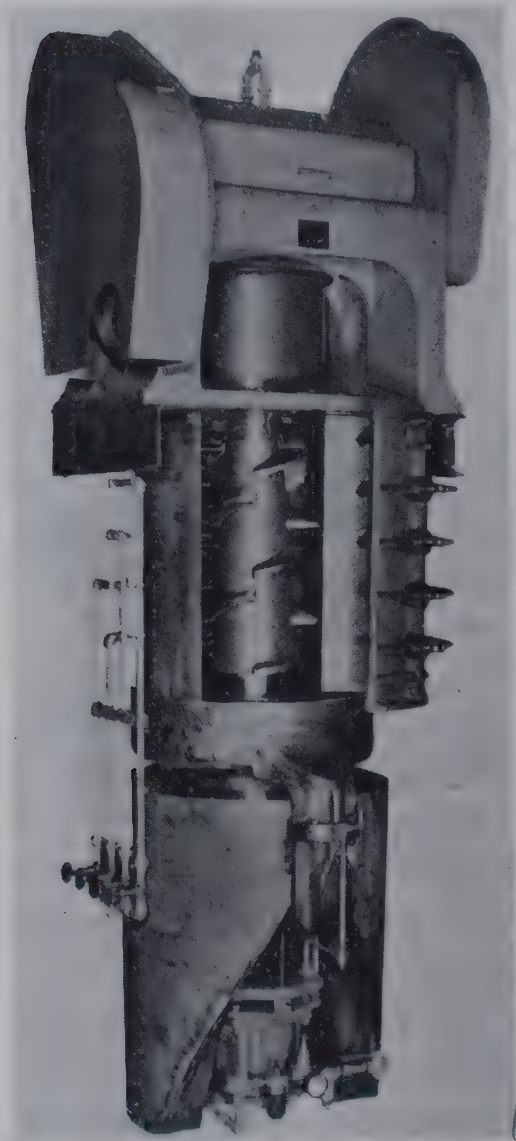
In the *curb press* the material is held in a perforated or slotted cylinder of wood or of metal, and pressure is applied by a ram entering the cylinder from the top.

Continuous Presses

Continuous presses for removing liquid from solids are made in several variations of two widely different styles. These are the screw press and the roll press.

The *screw press* is of increasing industrial importance. It will handle about the same type of material as the plate or curb press, will remove almost as much of the liquid, and needs less

labor. When processes are such that the press can be kept properly filled, this type of press operates very satisfactorily.



(Jackson and Church)

Figure 80. Screw Press; Vertical continuous type (Sectional view).

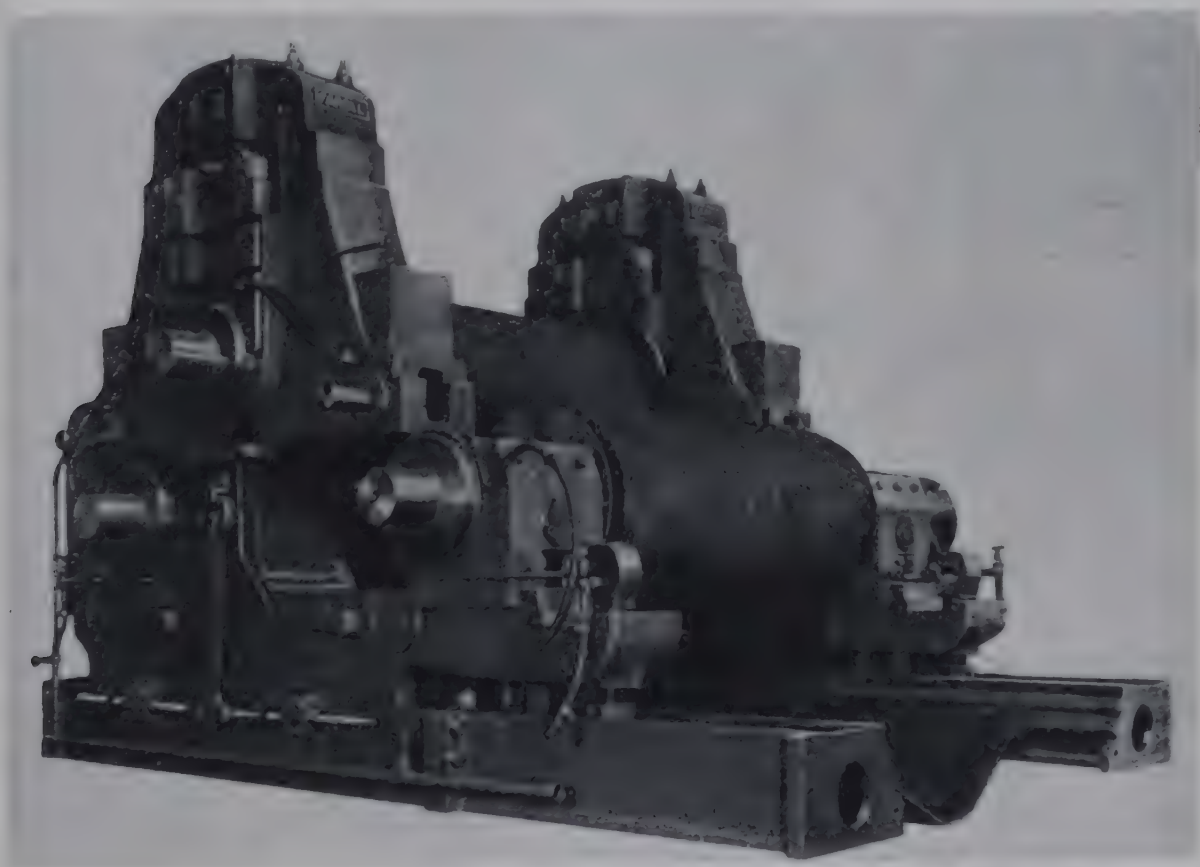
The screw press consists of a rotating screw which fits closely inside a vertical or horizontal perforated or slotted cylinder or cone. Pressure is applied by completely filling the intake of the screw and then decreasing the size of the open space in the screw as the solid is moved through it. This is accomplished by tapering both the screw and screen, or by using a cylindrical screen of uniform diameter with either a screw of decreasing pitch or a screw having a tapered shaft.

A second type of continuous press is the *roll press*, in which the material to be pressed is caught in the nip of heavy rolls. These rolls may be held together merely by their weight, they may be spring- or weight-loaded, or they may be held together by hydraulic pressure. The use of the roll press provides a rapid continuous pressing operation. Its major disadvantage lies in the very limited time the material is in the pressure zone. This may

be much too short a time to remove liquids of high viscosity which may be expelled quite slowly.

Removal of Liquid by Action of a Solvent. Solvent extraction is employed as widely for the separation of liquids from solids as for the separation of two solids. It has been found that many materials which respond well to separation by pressing can be so much more completely separated by solvent action that the greater yields of liquid and the drier condition of the solid justify

the additional expense. Solvent extraction methods have long been recognized as ideally suited for removing fats and oils from solid vegetable matters; but traces of solvent left in the oil after separation made the oil inedible, and small amounts remaining in the press cake rendered it unsuitable for cattle feed. Considerable research on this problem has developed solvents which have high dissolving power, are reasonable in price, and can be com-



(Farrel-Birmingham Co.)

Figure 81. Roll Press. Three Roll Sugar Mill.

pletely removed from both the oil and residue without leaving a trace of taint. This has been a great stimulus to the wider use of this process. An operation, essentially solvent extraction, is that of washing out water-soluble liquids with water.

The equipment used for this operation is similar to that for the solvent extraction of one solid from another. The solid can be held in a tank or tower and the solvent circulated over it, or the solid can be agitated in the liquid solvent.

One of the major difficulties in the solvent extraction of a liquid

from a solid lies in the fact that after the initial extraction is completed the solvent must still be separated and recovered from both the extracted liquid and the residual solid.

Removal of Liquid by Displacement. Although this operation is seldom used industrially, it is entirely possible in some situations, to displace one liquid from a solid mass by the introduction of another. This is particularly true if the first liquid is held by surface adsorption on the solid, and if the second liquid introduced into the solid mass is more strongly adsorbed than is the first. This is the general principle of a new technique, known as chromatography, for the separation of liquids; it will be discussed at somewhat greater length in the section dealing with liquid-liquid separation.

Techniques for Complete Removal of Liquid

Removal of Liquid by Vaporization. In order to obtain a solid free of liquid it is ordinarily necessary to vaporize the last traces of liquid present. In those cases in which vaporization of liquid is practically impossible and yet a dry solid is required, it may be necessary to take out the original liquid by solvent action and then remove the solvent by vaporization. Other possible solutions to specific problems should suggest themselves.

A volatile liquid may be removed from a nonvolatile solid by the application of heat or vacuum, or both (drying), or by introducing a second vapor, such as steam, whose condensed liquid is immiscible with the liquid being vaporized (vapor distillation).

Drying by Application of Heat at Atmospheric Pressure

Although drying generally refers to the separation of water from a solid mass, the same techniques apply to the separation of any volatile liquid from a solid. The major distinction between the removal of water and the removal of some other liquid usually lies in the requirement for salvaging the vapor of the other liquid, and the necessity, therefore, of drying in a somewhat different manner. Another important consideration in the selection of a drying method concerns the maximum temperature to which the mass may be heated. This may be so low that drying becomes

too slow, and consideration must be given to methods other than those involving the addition of heat.

One final point to be considered in the design of all dryers is that avenues of vapor release must always be provided. These vapors may be discharged by natural circulation, by forced circulation under atmospheric pressure, or by drawing them off through a vacuum pump.

Dryers in which material is dried at atmospheric pressure and without recovery of the vapor may be classified in general by the method, direct or indirect, by which heat is transferred to the liquid being vaporized. The most widely used method for water removal is direct heat, whereas for solvents or liquids other than water, indirect heat is almost always required.

Direct-heat Dryers. The direct-heat dryer, in which the material being dried comes in contact with the stream of air or gas conveying heat into the dryer, is the most widely used type of dryer. These dryers may be either intermittent or continuous in operation.

The simplest of all dryers is the one in which vaporization takes place in an unheated air stream (air drying). Heat may be furnished by the sun or may be supplied by the air itself as sensible heat, the air being cooled during the vaporization process. Air drying may be quite satisfactory for many materials, particularly for those which have a tendency to become sticky or change shape on being heated. Air drying equipment is usually little more than a means of exposing the material to free movement of air.

Another fairly simple drying arrangement is the *tray dryer*. In this dryer the solid to be dried is spread in thin layers in wood or metal trays and placed in a closed container resembling an oven. Heat is usually supplied by either the natural or forced circulation of air over steam coils. Air may be circulated over the surface of the material in the trays or through it by forcing it through perforations in the bottom of each tray. This dryer permits the control of humidity of the drying air as well as the control of temperature. This is an extremely important feature in that many substances check or warp if dried too fast, even in air dryers, and by controlling humidity this tendency can be greatly

suppressed. Accurate control of heating rates also may be essential to make adjustments in the drying rates. This is easily accomplished in the tray dryer.

Dryers of somewhat larger capacity than the tray dryers are designated *compartment dryers*. These are made to take small or large cars of material. The car is usually loaded outside the dryer and rolled into the dryer as a unit.

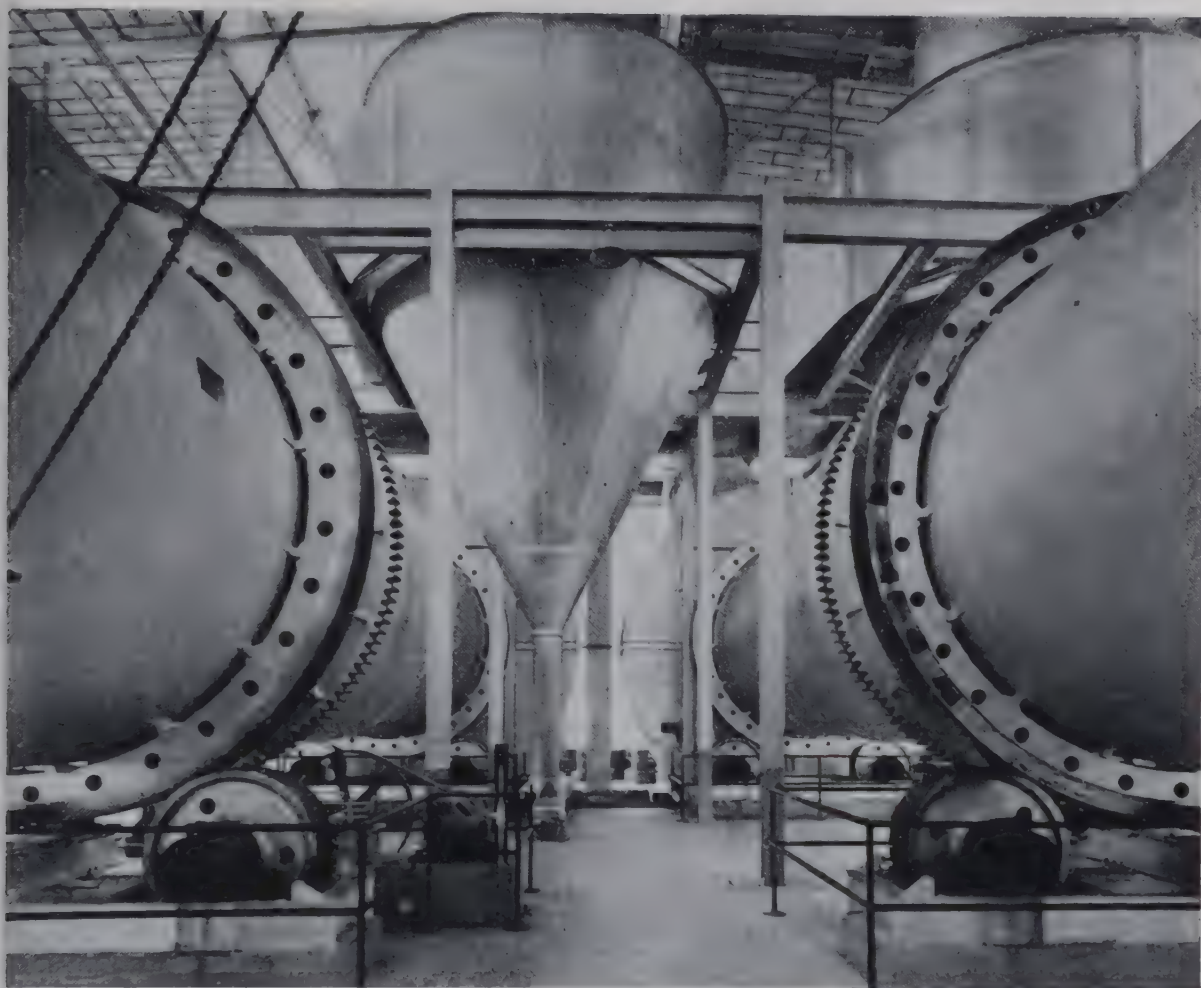
There are several types of continuous dryers in industrial use. These are, for the most part, of higher capacity than the batch dryers. In addition, continuous dryers give larger capacities per unit of floor space, and usually require less labor per unit of material dried. They are, however, somewhat less susceptible to accurate control of drying conditions.

One of the more important continuous dryers is the *tunnel dryer*—actually an elongated compartment dryer, usually fitted with rails running the entire length. Loaded cars can then be pushed in one end of the dryer while a car of dried material is ejected simultaneously from the discharge end. These dryers may be separated into a series of compartments for improving temperature control. *Belt dryers*, in which the material is spread on traveling belts which are moved through the heated space, are very popular.

Continuous tray dryers are available which are similar in general design to the Herreshoff roasters previously described. These dryers have a series of circular trays over which the material being dried may be slowly moved, either by rotating plows on stationary trays or by rotating trays against a stationary discharge plow.

One of the requisites of drying is to expose as much of the surface of the material to the stream of heated gas as possible. For materials which are not damaged by rough treatment, *rotary dryers* are very satisfactory. These are simply long tumbling barrels having axes slightly tilted so the material will move forward through the drums as they revolve. Movement of material through the dryer can also be accomplished by making the dryer in the shape of a truncated cone and arranging the axis in a horizontal position.

Many materials are produced in continuous sheets, which must



(Stearns-Roger Mfg. Co.)

Figure 82. Rotary Dryer Installation.

be dried before they are rolled. Coated papers, freshly dyed or treated cloth, and even light linoleums and many similar materials are dried by hanging them in festoons or by drawing them tautly through a large space through which heated air can be circulated. The festoons are often preferred, especially if variable shrinkage is likely to take place during the drying operation.

Many other types of continuous dryers have been developed for special uses.

Indirect-heat Dryers. In many cases it is inadvisable to pass heated air over the materials being dried because of possible heat and chemical damage, and inert gases may be too expensive to use on the scale necessary for direct-heat dryers. It may also be necessary, at times, to salvage the vapors from the dryers. Thus there is indicated the need for using indirect-heat dryers.

Batch-drying of material by indirect heat and at atmospheric

pressure is not too often done industrially, although it is perfectly practicable. One dryer for this service is the tray dryer in which the trays are placed on heated shelves or directly on steam coil platforms. Another type is the agitated pan dryer in which the material to be dried is placed in a pan heated from the under side. The material is agitated by means of plows or rakes which travel slowly through the mass, breaking up lumps, and turning the material so as to expose fresh surfaces to the drying action.

There are several styles of continuous indirect-heat dryers, some of them patterned closely after the direct-heat dryers. The continuous tray, in which the material is raked across heated plates, and the rotary dryers heated by steam jackets, internal steam coils, or other means, are two examples of dryers having direct heat counterparts. Another is the *belt dryer* which consists of a continuous fabric belt moving in close contact with a steam-heated platen. The material to be dried is placed on the belt and receives heat through it.

The *cylinder dryer*, one of the more important indirect-heat dryers does not have a direct-heat equivalent. This dryer consists of cylinders, usually steamheated, arranged in banks of 5 to as many as 50 in series. Heavy canvas belts press the material against the outside of the rolls unless the material itself is strong enough to be stretched tautly over the drying rolls.

Radiant-heat Dryers. There is considerable use at the present time of radiant-heat dryers, in which drying takes place on the surface without penetration of heat through the entire body. The use of radiant lamps in the drying of automobile and other industrial finishes is well known. The application of radiant-heat drying in the chemical field could probably be expanded.

Dielectric-heat Dryers. The use of high-frequency electricity to generate heat throughout a thick body has unusual interest in the drying of such material as lumber in which the surface is likely to dry first, and then not only check because it shrinks, but provides a nearly impenetrable barrier to the transmission of heat to the interior of the section.

The high initial cost of the dielectric heater and its low efficiency have discouraged its widespread use. The elimination of either or both of these features would quickly expand the field of application for this type of dryer.

Drying under Reduced Pressures

Many substances, particularly those organic in nature, are damaged by the heat necessary to effect drying at atmospheric pressure. For drying these substances, the application of a vacuum, which very effectively lowers the temperature at which vapor is rapidly discharged from the liquid-solid mixture, and which removes the vapor from the dryer as it is formed, has been found to be an extremely useful technique.

Slightly reduced pressure drying is often used for removing solvent vapors where it is desired to recover these solvents. Other than being closed so that vapor is not lost to the atmosphere, the units for this service are all similar to the indirect heat dryers.

The difficulty of handling solids in a continuous manner into and out of a space which is at a pressure materially different from atmospheric discourages the use of continuous dryers for use under vacuum. Hence, most vacuum dryers are batch wise, indirect-heat types built with tight closures to prevent leakage, and heavy enough to withstand the vacuum which is applied. Vacuum tray, rotary, and pan dryers are quite similar to their indirect-heat atmospheric pressure counterparts.

Because of the general desirability of handling materials continuously, there are occasions in which the solid is made fluid enough to pump by the addition of a small amount of liquid, so that it can be handled as a liquid and hence be more suitable for continuous drying. This procedure is sometimes quite practical and should be investigated as a possibility where continuous vacuum drying is required.

A new technique known as freeze-drying is also carried out under very high vacuum. Materials such as potatoes may be quick-frozen, and then dehydrated without being melted by sublimation of the water under high vacuum. A much superior product is obtained with respect to flavor and consistency, when thus prepared, compared with that obtained by direct drying, even under a vacuum.

Removal of Liquid by Vapor Distillation

In vapor distillation, a method is available for obtaining good transfer of heat to the solid mass from which the liquid is to be

removed; at the same time, it provides for vaporization of the liquid at temperatures well under the boiling point at atmospheric pressure.

The only requirement of the method is that the vapor passed into the mass is from a liquid which is immiscible with the liquid being driven off. The lowering of the boiling point is a consequence of the fact that, in such a mixture, the vapor pressure of each component is exerted independently of the other, and the mixture boils when the sum of the vapor pressures of the two liquids equals the pressure in the vessel. Further lowering of vaporization temperatures can be obtained by vapor distillation under a vacuum.

In the operation, the solids are placed in a closed vessel (still) and steam, usually superheated, is passed into it. Steam, together with the vapor from the liquid being removed, is led off the top and condensed. The water and the liquid product, which are insoluble in one another, are easily separated.

The major disadvantages of vapor distillation are low heat efficiency and the fact that the solid, at the conclusion of the extraction, is saturated with the liquid used for the process. If the liquid used for vaporization is expensive, it must be removed from the solid by further treatment.

SPECIAL CONSIDERATIONS IN THE SEPARATION OF LIQUIDS FROM SOLIDS

The concentration of liquid in the final product is important to the selection of the proper techniques to be employed in the removal of a liquid from a solid mass. The removal of liquid by centrifugal force or by pressing is much cheaper than removing it by vaporization; hence material should not be dried beyond the practical limit of these two general techniques unless special conditions demand it. In those cases where the content of residual liquid must be very small, it is recommended that these techniques should in general be used as a first stage to remove as much liquid as possible, with only the last small portions being removed by a second-stage vaporization process.

A point which should always be kept in mind is that many substances, such as lumber, paper, oil-cake residues, and others, are seldom dried to complete dryness, since on exposure to the air

they will regain moisture to establish an equilibrium moisture content of, say, 5 or 10 per cent, or perhaps even as much as 20 per cent depending upon the nature of the solid. There would be little object in going to the expense and trouble of complete dehydration in cases such as these.

In the removal of moisture and other liquids there may be a low liquid content below which it is unnecessary and uneconomical to go. If water, for example, is being removed to decrease weight and shipping costs, the distance the material is to be shipped and the freight rates may be the determining factors in fixing the practical extent of water removal. The same general economic considerations apply to other materials.

In the operation of many of these techniques, various precautions must be observed continuously in order to get excellent separation of liquid and solid and to obtain maximum recovery of both liquid and solid as high quality products. Overheating and scorching, detrimental to color and flavor, are common to methods of drying. Warping and surface checking of lumber will occur if drying rates are not exactly controlled. Dryers are easily overloaded so that complete drying is not obtained and products cake in the bag or box. The possibility of solids passing the retaining screen in any of the draining methods is always very real, and poor yields of solid and contamination of the liquid product are often obtained. Solids are also quite likely to contaminate pressed liquids, and those liquids must often be freed from small amounts of solids in subsequent operations. The problems of handling a sticky solid, or one which becomes sticky as it is heated or dried, may be enormous, and many types of dryers may be unsuitable because they cannot cope with these problems. The removal of liquid from some solids may be extremely difficult if the solid retains the liquid tenaciously, or if it is unusually fragile, or both.

16 : SEPARATION OF A GAS FROM A SOLID

Removal of Adsorbed Gases from the Surface of Solids

Techniques for removal of an adsorbed gas

Vacuum techniques

Inert gas techniques

Medium temperature techniques

High temperature techniques

Chemical techniques

While normally there is little interest industrially in the separation of gases from solids and the techniques for accomplishing their separation, there are a few cases in which the removal of gas from a solid is highly important.

Gases may exist as a blanket around a solid and can be withdrawn at will by exhaustion; or they may exist in permanent occlusion in the solid, or may be adsorbed on solid surfaces. The first situation involves no problems which cannot be solved by the application of any vacuum technique. The removal of gas bubbles from a solid is impossible, except by remelting the solid, and removing the gas from the molten mass. This, then, becomes a matter of separation of a gas from a liquid and the techniques involved are discussed in the appropriate section. This leaves only the third situation, that of the removal of adsorbed gases, as the subject for this particular discussion.

REMOVAL OF ADSORBED GASES FROM THE SURFACE OF SOLIDS

Some gases are tenaciously adsorbed on surfaces of certain solids—a property which is sought after in the removal of one gas from a gas mixture. However, the problems involved in the removal of a gas from the solid, particularly that of the regeneration of the solid to its initial adsorptive form, are frequently

extensive and complicated. Rarely is the gas present in sufficient quantity that its recovery is deemed necessary or profitable.

Since the techniques for the removal of an adsorbed gas are rather limited in number and variety, the selection of any technique depends essentially on a choice of any one which will effect the separation. Most of the other factors upon which the final selection of a technique may be based are of little relative importance.

Techniques for Removal of an Adsorbed Gas

In general, the amount of gas adsorbed at equilibrium on any solid surface is reduced with a reduction in the partial pressure of the adsorbed gas in the surrounding atmosphere, or by an increase in temperature, or both. These are the underlying principles of the ordinary industrial techniques for the removal of an adsorbed gas.

A gas also can be removed from a solid surface by displacement with another gas or liquid which is more tenaciously held by the solid; however, this principle is seldom of interest as a basis for an industrial method for separation of a gas and a solid, since it is usually necessary to regenerate the solid, and the more tenaciously held gas is likely to be more difficult to remove than the original gas which was adsorbed.

The techniques, then, which are most used are those which reduce the partial pressure of the gas, or increase the temperature of the solid, or do both simultaneously. Two methods are available for reducing the partial pressure: the application of a vacuum or the flooding of the equipment with an inert gas. An increase in temperature may be an adjunct to either of these or may be used alone as a gas-removal technique.

Vacuum Techniques. High-vacuum techniques are necessary for the complete removal of adsorbed gases. Because of the great expense involved, the use of high-vacuum techniques is limited to gas removal under circumstances where other methods cannot be used.

Actually there are only a few cases where it is necessary to remove all gases of every kind from a solid surface. This is essential in the manufacture of some of the newer electronic equip-

ment. Some of these are used gas-free, while others require filling with a very pure gas. Usually this is an expensive gas which could not be placed in the tube by ordinary gas sweep methods of replacement.

High-vacuum techniques for gas removal are not often required in the chemical industry, but they should not be overlooked as a possibility. The removal of adsorbed gas can often be expedited by heating the material or space to be evacuated. The equipment used for this separation consists of a container, in which the material to be freed of adsorbed gas may be placed, and a means of producing and holding a high vacuum on the system for the requisite length of time. More frequently than not, the vacuum is applied to a system whose boundaries are already defined; hence it becomes merely a matter of developing the vacuum required through the use of a vacuum pump of adequate capacity.

Inert Gas Techniques. A convenient method of removing many adsorbed gases is to blanket the solid with a gas mixture containing little or none of the gas which has been adsorbed. The partial pressure of the adsorbed gas is, therefore, very low, and the adsorbed gas, in attempting to establish an equilibrium with the gas at low partial pressure in the mixture of gases is literally vaporized off the surface. This technique can usually be improved by an increase in temperature.

Portions of the inert gas are often simultaneously adsorbed on the solid surface as the surface is freed of the original gas. Unless it is necessary to remove gases completely, this readsorption of the inert gas is of little consequence, since it is easily and quickly replaced by the first gas when the solid is reused for gas adsorption.

Moderate-temperature Techniques. Since it is often difficult, particularly in the case of moisture adsorption, to supply an inert gas free of the adsorbed gas, use is made of the convenient feature of most gas-adsorption processes that an increase in temperature will usually cause a marked reduction in the amount of gas adsorbed at equilibrium. With an increase in temperature a satisfactory reactivation of the adsorbent can often be achieved without any change of the partial pressure of the adsorbable gas in the gas mixture. Therefore, somewhat elevated temperatures

are frequently used alone to remove adsorbed gases from solids, as well as to supplement high-vacuum or inert-gas techniques.

The reactivation of alumina, silica gel, or one of the other adsorbents used for air or gas dehumidification is typical of the operation and equipment required for the separation of an adsorbed gas. When the moisture content of the gas being passed through a dehumidifier shows moisture contents above those to which it must be dried, the adsorber is cut off the line and reactivation (removal of the adsorbed water) started. Air at an elevated temperature, as high as 350°F. for silica gel and somewhat lower than that for alumina, is passed through the mass of solid adsorbent, usually in a direction opposite to that in which the water-containing gas mixture was originally passed. After a time, usually gaged by experience, the solid is judged to be free of moisture and ready for re-use.

The equipment in which the removal is carried out is, of course, the same as that in which adsorption of the moisture took place. This equipment consists essentially of a steel tank in which the solid adsorbent is held on perforated trays. Steam coils or electric heating elements imbedded in the material on the tray may be used to provide the heat necessary for the reactivation, or the gas may be heated externally.

In some cases it may be necessary to remove adsorbed gases from a solid in equipment used solely for that purpose. Almost any dryer for removing liquids from solid masses will usually be satisfactory for the purpose.

An inert and high-temperature gas in the form of saturated or superheated steam may sometimes be used effectively for stripping an adsorbed gas from a solid adsorbent. Many of the hydrocarbons or other organic gases can thus be removed from solid adsorbents.

The use of steam as a gas for this operation is of interest from a safety standpoint when removing flammable gases from a solid. Steam at any temperature above the boiling point is a cheap non-combustible vapor, and is thus ideal for this use if the character of the solid adsorbent will permit it.

High-temperature Techniques. The simplest and cheapest method in those cases wherein the solid is not damaged by con-

siderably elevated temperatures is to heat the solid to such a temperature that the gas is driven off. The techniques are still further simplified if the solid has great enough structural strength to resist disintegration in moving it through a kiln.

Adsorbed gases can be removed from such materials by passing them through oil- or gas-fired rotary kilns, Herreshoff type multiple-hearth furnaces, or cascade-type furnaces. They may also be heated by passing them through tubes externally heated to the temperature required.

The application of this technique is always accompanied by considerable risk. Most solid adsorbents are sponge-like in structure, honeycombed by great numbers of microscopic pores in order to provide the huge surface which is required for efficient adsorptive action. If, during the gas removal process, these pores are closed, the medium may be destroyed for further use as an adsorbent. Sometimes temperatures many degrees below the melting point of the adsorbent will soften the medium enough to close these pores. In the removal of many adsorbed gases a similar action may take place by chemical reaction of the adsorbed material with the medium, or by polymerization of the adsorbed gas.

Chemical Techniques. A change in the chemical nature of the adsorbed gas and hence an alteration of its adsorptive character can sometimes be wrought by chemical action.

When, for example, the adsorbed gas is combustible, it is quite possible, and often practicable, to burn off the adsorbed gas. There is usually not enough gas adsorbed to support combustion, but it is sometimes possible to heat the solid in an atmosphere containing enough oxygen to oxidize the adsorbed material. The danger of sealing the adsorptive surface is present here even more than in the use of the direct heat, since localized temperatures on the surface of the solid may be well above the measured temperature of the gas stream.

The equipment used for this process can be identical to that used for the high-temperature removal techniques.

17 : SEPARATION OF A SOLID FROM A LIQUID

Techniques for Separating Solids from Liquids

Techniques for separating a dissolved solid from a liquid

Based on relative vapor pressure of solid and liquid

Based on phase relationships of solid and liquid

Based on relative solubility in immiscible solvents

Based on reduction of solubility

Based on chemical precipitation

Based on ion-exchange properties

Based on electrolytic deposition

Based on adsorptive properties

Techniques for the separation of solids in suspension from liquid

Based on difference in density

Based on cross-section of the solid particle

Based on the electrostatic properties of the solid

Techniques for the single-step reduction of a solution or slurry to a dry solid

The removal of a solid from a liquid is one of the most frequently encountered operations in the chemical field; virtually no chemical or process industry conducts a chemical process in which it is not required.

There are two fundamentally different situations relating to the condition of the solid in the liquid medium: (1) the solid may be dissolved in the liquid, or (2) it may be insoluble and suspended in the liquid. Wherever undissolved material is present, the liquid may usually be assumed to be saturated; in this case, there is always solid both in suspension and in solution in the liquid phase.

Another point to consider is the fact that there can be varying degrees of separation which may meet specifications of purity. Further, a complete separation may sometimes be effected in one step, but normally it requires two or more separate steps to complete the operation.

A number of factors relating to the solid, the solution, and the final requirements of the process will affect the choice of a technique for the separation. Certainly one of the most important concerns the condition of the solid in the liquid—whether it is in solution or whether it is suspended. Other more important factors to be considered are as follows:

1. Relationship of the solid to the liquid
 - a. Solid in solution in the liquid
 - aa. Concentration of the solid in the solution
 - bb. Solubility
 - cc. Solubility-temperature relationships
 - dd. Viscosity of the liquid medium
 - b. Solid in suspension in the liquid
 - aa. Relative amounts of solid in suspension
 - bb. Size of solid particles
 - cc. Density of solid particles
 - dd. Compacting properties of solid
 - ee. Viscosity of liquid medium
 - ff. Nature of solid, whether gritty, sponge-like, etc.
2. The degree of separation required
3. Heat-sensitive properties of the solid or liquid
4. Whether it is necessary to recover the solid, or liquid, or both in uncontaminated form
5. Value of recovered solid or liquid
6. Amounts of material to be treated
7. Corrosive properties of liquid

TECHNIQUES FOR SEPARATING SOLIDS FROM LIQUIDS

Because of the variety of process requirements and the large number of chemical and physical principles upon which techniques for separation of solids from a liquid system can be based, classification of the techniques is difficult. To make some division, there will be considered (1) the means of removing solids from solution, (2) solids from suspension, and (3) the single-step reduction from solution to a dry residue.

Techniques for Separating a Dissolved Solid from a Liquid

A number of chemical and physical principles can be applied to the separation of solids from solution. Purely physical proper-

ties lead to several successful and widely used techniques; some of these are:

- a. Relative vapor pressure of solid and liquid
- b. Phase relationships of various crystalline forms of the solid. Temperature-solubility relationships
- c. Relative solubility of solid in immiscible solvents
- d. Alteration of solubility by:
 - aa. Addition of second solvent
 - bb. Addition of a common ion
- e. Precipitation of solid by chemical precipitant
- f. Chemical action of ion exchange
- g. Electrolytic properties of the dissolved solid
- h. Effect of adsorbents on the dissolved solid

In this discussion it must be understood that the recovery of a solid relatively free from contamination by residual liquid will normally require additional steps employing techniques for the separation of suspended solids from a liquid, or of a liquid from a solid, or both.

Techniques Based on the Relative Vapor Pressure of Solid and Liquid. Many solids dissolved in liquids have an exceedingly low vapor pressure relative to that of the liquids in which they are dissolved. If the solids are insensitive to the temperature of the boiling point of the liquid, the liquid can be easily vaporized to leave a dry residue. There are no basic principles other than this involved in the separation. Since this method of separation is applicable to solids in suspension as well as to those in solution, it will be described more fully in the section of this chapter dealing with the single-step reduction of solid-liquid system to a solid residue.

Techniques Based on Phase Relationships of Solid and Liquid. The principles involved in the separation of dissolved solids by phase relationships, particularly the temperature-solubility curves, lead to many very efficient and practicable techniques for the separation of materials in solution. Sometimes these phase relationships involve a number of crystalline forms and become amazingly complex. Nevertheless, they are frequently applied to the separation of materials.

The process whereby solid material is precipitated by causing

the solution to become supersaturated and deposit solid is normally called crystallization. The conditions for promoting crystallization are obtained by cooling of the solution, by concentrating it, or by both concentrating and cooling.

Crystallization by Cooling Alone. If cooling in a reasonable degree will cause crystallization to take place, it should be considered first. Not only is it usually cheaper to cool most solutions, but the deleterious effects which elevated temperatures may have on both the solid and liquid are avoided. Because of the latter feature, some solutions are cooled to very low temperatures to effect partial or complete crystallization of the solid portion.

The techniques for separation of solid from liquid through crystallization by cooling become, in fact, the techniques of cooling and refrigeration, together with adequate heat transfer, and agitation to develop uniform temperatures throughout the mass.

These procedures may be greatly complicated by the fact that many solutions, even those which may be fairly fluid at room temperature, become very viscous at the temperatures required for crystallization. The highly viscous solution increases the difficulty of heat transfer and distribution, tends to inhibit the formation of crystals, and creates complex and difficult problems attending the separation of the crystals of solid from the remaining solution when crystallization is complete.

The devices used for carrying out this technique are known as crystallizers. They are more than likely to be batch units having heavy, slow-speed agitators. Temperature control is usually obtained by circulating coolant through a jacket surrounding the crystallizer, or through the agitator, or through both. Cooling coils within the crystallizer are usually avoided, if possible, particularly if the final mass is viscous. Several crystallizers of this type are nevertheless available, a helical cooling coil operating in a horizontal tank being typical of the group. For occasional or even continuous use, an ordinary jacketed kettle provided with a slowly rotating agitator can be used very effectively as a crystallizer.

The major advantages of the batch crystallizer are that the material can remain in the unit for any period of time required,

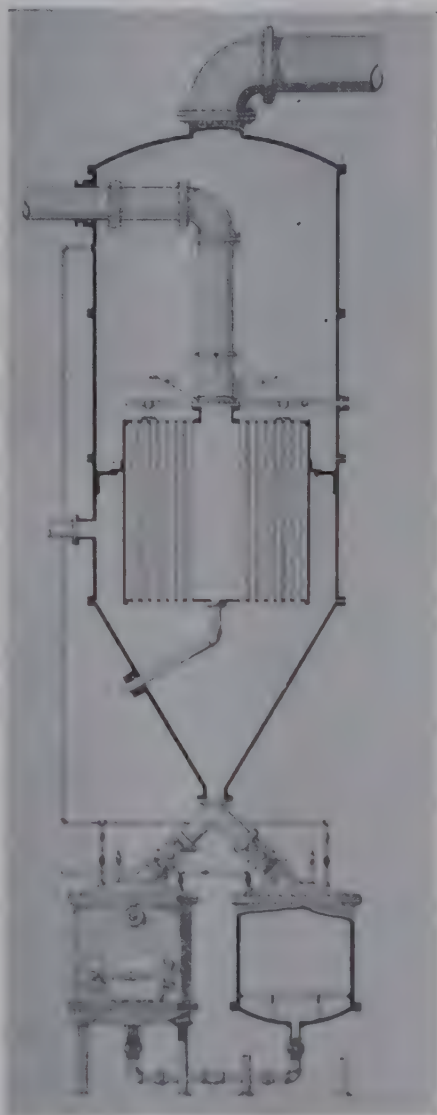
and can be discharged when it has been determined that the proper crystal size has been reached. The first advantage is of considerable interest, since it may require from 2 to 5 days to complete the crystallization process. The second is important in those cases in which it may be necessary to produce a very carefully regulated crystal size.

Continuous crystallizers have been developed to provide the convenience and lower cost of operation of a continuous process. These are best in cases where continuous production of material is desirable, where crystal formation is relatively rapid and crystal size is not important.

Crystallization by Concentration.

Some substances, notably common table salt, have remarkably flat temperature-solubility curves, and consequently resist crystallization by cooling alone. Any substance not affected by heat, having a low vapor pressure and dissolved in a liquid, such as water, which has a relatively high vapor pressure, can be separated from solution by vaporizing the solvent. Concentration of material by the application of heat is conducted in equipment varying from open ponds exposed to the sun for heat to the most modern multiple-effect vacuum evaporators.

Closed evaporators are widely used at the present time for the concentration of many substances. The only reasons for closing an evaporator removing water from a solution are either to allow it to be operated under a pressure different from atmospheric and, therefore at a temperature different from the normal boiling point, or to permit the use of vapor from one evaporator as a



(Svenson Evaporator Co.)

Figure 83. Vertical Tube Evaporator. Basket type with salt receivers.

source of heat for the next. These evaporators, known as multiple-effect evaporator systems when connected in series, are used for concentrating solutions, either as a preliminary to crystallization, as a means for inducing crystallization within the evaporator, or merely for the removal of a liquid from a mixture of liquids.

Of noteworthy interest in this connection is the possibility of concentrating solutions at temperatures well below their normal boiling points. This is accomplished by applying a vacuum to the system. The vacuum pan and vacuum evaporators are used virtually everywhere in industry where it is necessary to concentrate solutions.

Crystallization by Concentration Followed by Cooling. It is a normal procedure in the separation of solid materials by crystallization to concentrate the solution by evaporation and then to separate the crystals by cooling the solution. The process may be repeated on the liquor which is left after the first crop of crystals is taken, and further repeated until the solution becomes so filled with impurities that crystals which are formed become contaminated. Impurities in the mother liquor may also inhibit crystal formation.

By this procedure, evaporation and crystallization can be conducted at temperatures well below those at which the last of the solvent would be driven off. It is also of interest that solid impurities in the solution can be drawn off in the liquor and are not brought down with the crystals, as they would be if the solution were evaporated to dryness.

Crystallization by Simultaneous Concentration and Cooling. Concentration, cooling, and crystallization can often be made to take place simultaneously by evacuating a vessel in which a solution is held.

Further, at high vacuum, solvents may be removed at temperatures far below their normal boiling points. Water, for example, can be evaporated at temperatures below the freezing point. The process known as freeze drying has been developed to exploit this phenomenon. Materials such as penicillin, fruit juices, and several others are so highly heat sensitive that attempts to reduce them to a dehydrated product by ordinary evaporative processes have been quite unsuccessful; food dehy-

drates lose flavor and body, and pharmaceuticals suffer loss of potency.

The success of the processes using extremely high vacuum for the vaporization of water is due to advances in the design of low-temperature condensers for trapping the water vapor and development of procedures for supplying heat to the frozen matter in the quantities required for the vaporization.

The importance of the low-temperature condenser is evident when it is pointed out that one pound of water occupies 15,000,000 cubic feet at a pressure of one micron. Thus tremendous volumes of gas would have to be moved if the vapor passed through a pump, and the size and cost of pumps required to evacuate even a low-capacity evaporator would be enormous.

To solve this problem, *refrigerated ice traps* are used. One commercial pattern has a rotating surface cooled by an industrial refrigeration system. Vapor in the gas is cooled and condensed as ice on this surface. It is removed by scraper blades. With this condenser in the system, the vacuum pump has only to remove the noncondensable gases and any air which may leak into the equipment.

Another ingenious method for removing water vapor is the use of a refrigerated brine, such as lithium chloride brine, in a spray chamber. The brine takes up the water vapor, and is conducted out of the system. It is then reconcentrated by heat, re-cooled, and is ready for use again.

Techniques Based on Relative Solubility in Immiscible Solvents. Many solid materials in solution may be extracted by transferring them to a second solvent, the solvents being mutually insoluble. While these techniques do not produce a solid, they can be used to remove a solid from one solution or solvent and transfer it to another in which it may either be in higher concentration, or from which it can be more easily removed as a solid, or both.

The relative solubility of a substance in two solvents represents an equilibrium condition which depends upon the relative solubility of the material in the two liquids and upon the quantity of solute present. The actual transfer of a dissolved substance from one liquid system to another is a process involving

well-known principles of mass transfer; they may be accelerated by the same means which will speed up chemical action. Intimate contact between the two liquid phases is essential in this process. Further, the greater the difference between the actual concentration in the two liquids and that at the equilibrium distribution, the more rapid the transfer will be. For this reason, solvent extraction is almost always conducted as a countercurrent process. Equipment designed for this purpose usually provides for these two requirements, good contact and countercurrent movement of the liquids, and often includes provision for temperature control. The design of equipment used for this process is not standardized, since actually many types of apparatus can be used successfully to bring about the desired results.

Favored equipment types include continuous turbine agitators and columns. The column may be used without packing or baffles, in which case one liquid is sprayed either downward or upward, depending upon the relative densities, through the other liquid, which is pumped through the column. The baffle plate design gives very satisfactory results. Packed columns are not as useful in this situation as they are in effecting the contact of gases and liquids. Columns of considerable height are often used in order to provide sufficient time of contact between the two liquid phases to make the transfer of solid virtually complete.

Batch operations in which the two liquids are simply agitated thoroughly in contact with one another are also used in making extractions. They are especially useful where an extended period of contact between the liquids is necessary to procure adequate transfer of material.

Solvent extraction techniques are becoming much more widely used as new and better solvents become available and as the principles of the operation are more thoroughly understood. They are used particularly in the petroleum industry, where paraffinic and asphaltic substances are successfully removed from heavy lubricating oils—an operation which defies almost any other method of solid-liquid separation.

Techniques Based on Reduction of Solubility. Many solid materials can be driven out of solution by altering the condition

of the solvent. At least two techniques are available for reducing the solubility of a solid in solution. One of these consists of the addition of a second solvent, miscible with the first, in which the solid in solution is relatively insoluble. The other technique, known as the "common ion" effect, is based on the fact that a substance in solution, if ionized, can be suppressed in solubility by adding a highly ionized second substance having one ion in common with the original dissolved solid.

Occasionally, profound changes in solubility can be created by the addition of relatively minor quantities of a second solvent. More frequently, however, the second solvent must be added in sufficient quantities to materially alter the condition of the original solution. Since the second liquid must usually be removed from the first after the separation of the solid, the problems and expense involved in this removal are often great enough to discourage the use of this technique.

The common-ion technique for separation of solids currently has a much wider field of application. Many sodium or other metallic salts of organic acids such as soap and organic dyes can be removed almost quantitatively from a solution in water by saturating it with ordinary salt or other inorganic salts. This provides an effective and relatively inexpensive method of separation of materials like soap, which are low in cost, and yet so highly heat-sensitive that precipitation by concentration is out of the question. The salt may be recovered by evaporation, and little material loss is experienced.

The equipment used to carry out these techniques can be quite simple. Tanks of adequate capacity provided with agitators are usually all that is necessary. Some materials require a certain length of time to collect at the top or bottom of the treating tanks, and sufficient storage capacity must be provided to allow adequate settling time.

Techniques Based on Chemical Precipitation. Many solids in solution which fail to respond to the strictly physical means of separation may be separated by chemical conversion to an insoluble precipitate. However, unless the chemical used is extremely low in price, like air or water, the costs may be exorbitant. In this separation, too, there may be further problems and expense

involved in the separation of the chemicals from the residual liquor.

Nevertheless, chemical precipitation of solids from solution is often practiced. This is particularly true when the solid in solution is present in minor quantities (perhaps considerably less than 0.1 per cent), and while it could be removed by evaporation it would not be profitable to do so because of the large quantity of solvent which would have to be evaporated for such a small amount of solid.

Although numerous chemical materials can be used for precipitation, economic considerations usually limit the use to one of a small group of chemical substances. Limestone, from which both calcium oxide and carbon dioxide can be easily and cheaply prepared, is one of these. Both lime and carbon dioxide can be used to precipitate many chemical compounds, either as insoluble calcium salts or as carbonates. They both have further interest since in many cases the calcium salt which is separated can be decomposed by carbon dioxide, and carbonate precipitates can be often changed back to their original condition by the addition of lime to the compound, the lime removing the carbonate as calcium carbonate.

Other precipitating agents of a more expensive type can be used profitably in those cases wherein the quantity of substance to be precipitated is small, the material to be recovered is expensive, or the precipitating agent can be cheaply and easily recovered.

Industrial equipment in which precipitation may be carried out may be arranged for either continuous or batch operation, both procedures being widely used. Batch operations are often favored, however, for the somewhat better control and longer retention time which can be secured.

Techniques Based on Ion-exchange Properties. It is a well known fact that several solid substances have the property of exchanging one ion for another if placed in a solution containing the ions. The first ion-exchange materials were the zeolites, still used widely for sodium-calcium exchange. Many synthetic resins and other materials have proved to have marked ion exchange properties.

Ion exchange is usually conducted as a batch process. The solution being treated is passed through a stationary or fluidized bed of exchange material until the bed is exhausted. Reactivation follows to complete the working cycle. Because of the relatively high operating expense per unit of material removed from solution, ion exchange is limited to fairly dilute solutions, and is normally used for purification with no thought of recovery of the solids removed in the process.

Techniques Based on Electrolytic Deposition. It is quite possible to separate a metal from a solution by electrolysis. The process has been discussed both as a mode of reaction and as a method of separating solid from solid, so there is little reason to elaborate further on the process at this point. The removal of metal can be quantitative. As a matter of fact, an analysis for some metals can be carried out by completely electrolyzing a solution of the metal.

Techniques Based on Adsorptive Properties. Some substances, silica gel and activated charcoal, for example, have the property of adsorbing certain solids in solution. Such solids can be removed by an adsorbent. Occasionally, the adsorbent bed is discarded after being saturated with the impurity; more frequently it is washed, heated, or otherwise treated to remove the adsorbed material. This method of removal of solids has been widely adopted for the removal of colors, flavors or odors of materials such as syrups, vegetable oils, pharmaceuticals and foodstuffs.

Techniques for the Separation of Solids in Suspension from a Liquid

The separation of suspended solids from a liquid medium is an unusually important industrial operation. There are fewer basic principles available for developing techniques for this separation than there are for the separation of solids in solution. However, since the physical characteristics of the solid and liquid are both important in the design of equipment, the number of designs of industrial apparatus available for this separation is quite large. The principles employed are (1) the difference in densities of solid particle and liquid medium, (2) the difference in cross-

section of a solid particle and liquid molecule, and (3) certain electrostatic properties.

Techniques Based on Differences in Density. The methods in use for the separation of solid materials from a liquid medium by difference in density between the solid and liquid are numerous. Their differences are based largely on the size of the particle and the speed at which it will settle through the liquid, and to some extent on the amounts which are initially present in the suspension.

Finely divided solids are most difficult to separate, especially if the liquid medium is somewhat viscous. Hence, most of the variations in procedure are related to the several methods for removing the finely divided materials. In addition to gravity settling, there is one process in which separation is obtained by artificially weighting the solids, and another in which gravitational forces are supplanted by centrifugal force.

Separation by Gravitational Settling

Many solids settle quite readily in the liquid in which they are suspended. Equipment in which settling can be effected is quite simple, the major differences in its design being based on the methods of withdrawing the solids after they have settled.

Separations in which the Solids Remain in the Separation Unit. If only a small quantity of solids is held in suspension and if they have no commercial value, they can often be left behind in the separation unit to be removed periodically and discarded. One of the best known of such settling units is an ordinary lake. Water in a lake will slowly clear itself of suspended solids, and, except for natural agitation provided by wind or animals, it would in time probably become completely separated from all noncolloidal solid material.

Small *settling basins*, many of them concrete or steel-lined, are also used. The basin may be operated either as a batch operation, the clarified liquor being withdrawn periodically from the unit, or it may be removed continuously at some location remote from the point of liquid entry. The solid which accumulates is removed at intervals by either flushing or scooping it out.

Many solids which are moved along by a flowing stream of

liquid travel close to or at the bottom of the stream, where they can be trapped in depressions in the bottom of the channel, or on a roughened surface applied to both bottom and sides of the trough.

The use of settling basins or troughs is usually limited to material which is present in very small quantity, and is of most interest in those cases where settling is reasonably slow and the settled material is neither obnoxious nor valuable.

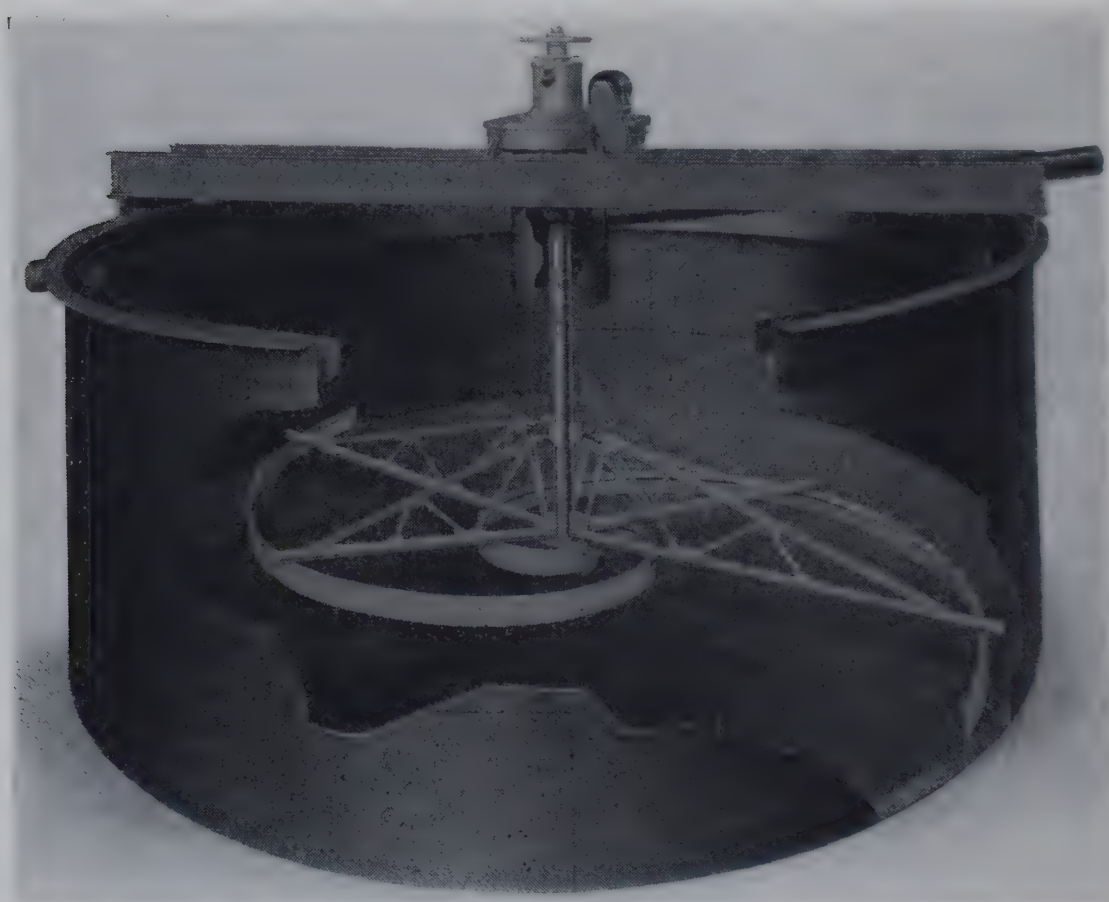
Separation in which the Solid is Discharged Intermittently or Continuously through the Bottom of the Unit. A number of commercial units are built which are provided with means of withdrawing the solids from the bottom of the unit without emptying the contents or interrupting the settling operation. It is necessary that the settled mud in these units be so finely divided as to be readily floated in a liquid.

Perhaps the simplest equipment are V-shaped or conical tanks to the bottom of which are attached mechanically or manually operated valves. Solids are withdrawn through these valves while the clarified liquor overflows the top. These are *decanters*, although they are made in several patented styles and given such names as clarifiers, thickeners, and settlers. Both manually and automatically operated decanters are available.

The *cone decanter*, having steeply sloping sides in order to deliver the solids to the discharge valve, requires special construction and has a very small capacity per unit of area. A tank has larger capacity, but the discharge of solids in the same manner as done in the decanter is impossible. To provide large capacity plus positive solids discharge, tanks provided with slowly moving plows are available. These are called *thickeners*. The several styles of thickeners are differentiated largely by the type of mechanism used to plow the solids to the center discharge. They are otherwise very much alike. All consist of a low form tank, having a bottom moderately sloped toward the discharge. The feed is introduced through a central tube, and the clarified liquid passes radially outward from the center and overflows into a channel surrounding the tank. The solids which settle are pushed slowly toward the discharge pipe near the center by slowly turning arms to which plows are attached. Any solids which float, such as sticks, trash, and other material, may be scooped off and

pushed into another discharge by an arm which floats on the surface.

When space is at a premium, a *rectangular clarifier* may be desirable. Here a rectangular tank replaces the circular tank of the ordinary thickener and a scraper is pulled slowly along the bottom. A pusher arm at the top sweeps the scum from the surface. Flow is across the tank.



(Hardinge Co., Inc.)

Figure 84. Thickener; Spiral rake type.

It was noted some years ago that two shallow thickening tanks would give much greater capacity than a deep one of the same diameter. This observation has led to the development of several styles of so-called multicompartment or *tray thickeners*, in which relatively shallow thickeners are set one above another to make a series two to six compartments high. Rotating arms move the material across each tray in much the same manner as in the larger single compartment thickeners. The compartments may be operated in series, or in parallel.

Solids Discharged Continuously over Rim of Settling Tank. Solids which are large enough and heavy enough to settle to a

heavy layer in the bottom of a settling tank may be pulled up a slope from the bottom of the tank and discharged over its rim. The general type of equipment used for this purpose is known as classification equipment; there are several varieties of classifiers in commercial production. While the ordinary *classifier* is used most frequently to separate a free-settling solid from one which settles with difficulty, and has been described in that connection, it is essentially a mechanical device to remove a settled solid from a liquid medium. Mechanisms such as rakes, drags, spiral conveyors, and others are used for moving the settled solids out of the liquid.

Separation by Weighting

A solid suspended in a liquid is often so finely divided that it will not settle in any reasonable length of time. This material can sometimes be swept from the liquid by means of another precipitate which can be formed in the liquid in large loose conglomerates called flocs. Colloidal matter in domestic water supplies is nearly always removed by such preliminary treatment prior to filtration. The flocculant precipitate in water treatment is usually formed by adding lime and alum to the water. Other chemicals are used for similar results with other separations. Settling usually takes place in ordinary settling tanks or basins, or in thickeners of standard design.

There are some precautions which must be taken in the addition of chemicals so as to produce the best type of floc. Also adequate tank volume must be provided to give proper retention time for floc formation and the mixing and settling steps.

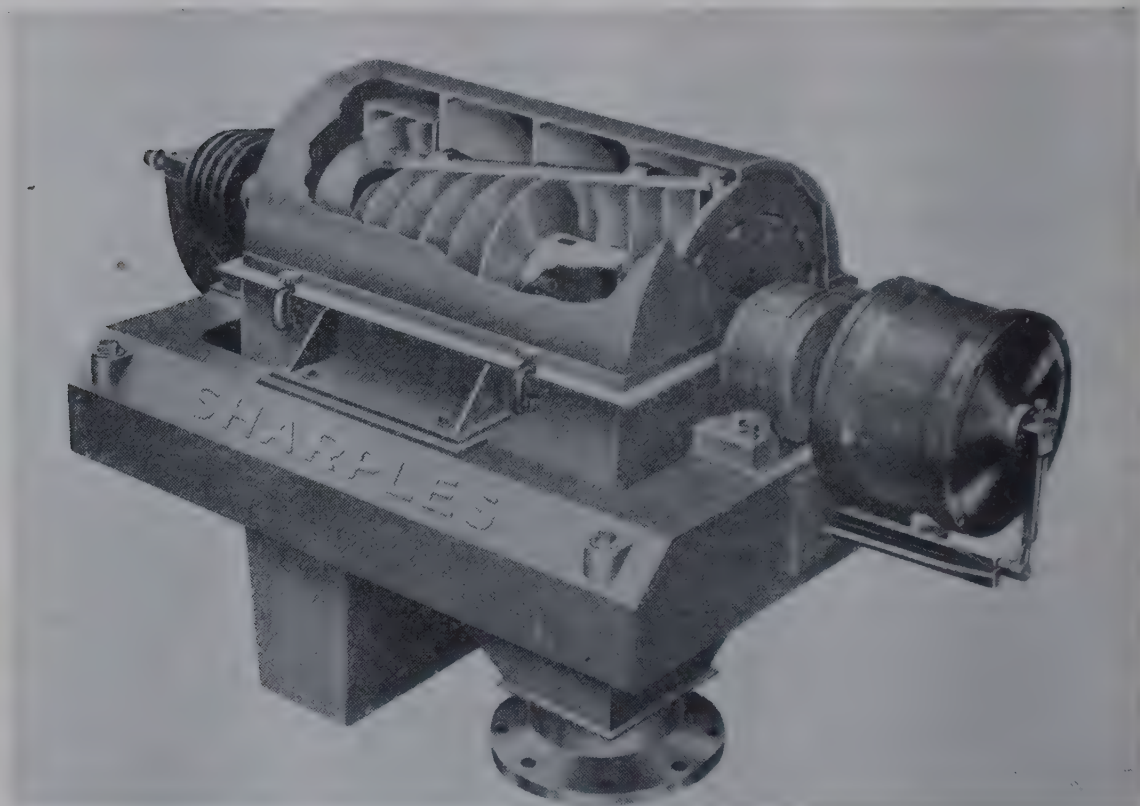
Separation by Centrifugal Force

Many solids too fine to settle or suspended in liquids too viscous to permit gravity settling can be concentrated by centrifuging. If the liquid containing the solid is whirled in a cylindrical bowl, a layer of a slime or mud containing the bulk of the solid forms at the wall and can be removed by skimming the whirling mass. Several models of *solid bowl clarifiers* are available.

Techniques Based on the Cross-section of the Solid Particle.

Some solid materials are so close to the density of water or their suspending medium that they settle with extreme difficulty. Also

the solids in suspension may be too concentrated to make settling an effective means of separation. In other cases settling may be too slow, or almost impossible because of the high viscosity of the liquid. It may be desired to remove the solids in a condition much freer from liquid than can be obtained by settling methods. Any



(The Sharples Corp.)

Figure 85. Centrifugal Decanter. Solid bowl clarifier.

of these problems can be solved by using one of the several types of filters available for separating solids from a liquid in which they are suspended.

Filtration is not too satisfactory on very dilute suspensions, and may give unusually difficult operating problems if the material being separated is slimy rather than crystalline in character. However, filtration is widely used, either alone or in conjunction with other methods of separation.

A filter consists of two essential parts: (1) a filter medium, which has holes large enough to permit the passage of liquid but small enough to retain the solid, and (2) a means of forcing

the liquid through the medium. Devices to remove the deposited solid, to drain away the filtered liquid, and to wash the solid are found on most filters.

The major differences in filters relate to the manner in which the liquid is forced through the filtering medium. There are three major classifications of filters: (1) the gravity filters, in which the liquid is driven by difference in liquid level on the two sides of the filtering medium; (2) the group of vacuum filters in which the liquid is drawn through the medium; and (3) the class of filters in which the liquid is moved by positive pressure through the filtering surfaces.

Each type of filter has a rather specific field of application. The gravity filter is usually limited to removing easily filterable substances, such as crystalline solids, large lumps, or matting fibers, out of a liquid of low viscosity such as water; or for separating colloidal material in minute quantities from a liquid.

Vacuum filters find widest use for separating easily filterable substances from liquids of low or medium viscosity. Since they are usually used as continuous filters, they are best adapted to the handling of very thick slurries of solids in liquids.

Pressure filters are best for use with liquids of high viscosity, for small amounts of solids, and in those operations wherein the solids must be subjected to prolonged washing periods.

The filtering medium may be a cloth made of cotton or other textile fiber, woven wire, or glass; or a surface of paper, felt, cotton batting, or porous rubber; or even porous blocks made of carbon, silica, or porcelain. It may also be a graduated bed of gravel and sand, the actual filtering medium in this case being a very thin layer of deposited solids on the top of the filter surface. Built-up media, consisting of metal bars supporting a coarse wire screen which in turn holds a finer wire screen over which is placed the actual filtering medium such as a cloth or paper, are often used, especially on vacuum filters which are likely to have large open filtering surfaces subjected to the possibility of considerably greater mechanical damage than most filters.

A practice which is common to virtually all types of filtering operations is the use of filter aids. Substances in suspension are

frequently of such a slimy character or are so finely divided that they do not readily deposit on a filter surface, and when they do, are apt to form a tight almost impenetrable film over it. This deposit may be so dense as to retard greatly the flow of liquid, or if thick enough, to stop it completely. Consequently, filter capacity and the rate of separation of the solid and liquid is substantially reduced. To overcome these difficulties, filter aids, such as diatomaceous earth or similar materials, are often added to the liquid before filtering. These are loose, finely-divided solids. They quickly form a secondary filtering surface over the cloth or other primary surface, and hence prevent the passage of any appreciable quantity of precipitate through the filter surface. When deposited with the solid to be filtered, they prevent the cake being compacted.

Very small quantities of a filter aid will usually suffice to assist the filtration greatly and their use usually so improves the filtering operation that cost is rarely a substantial item. Some can be reclaimed for further use. However, one factor which must be taken into consideration is that the filter aid leaves the operation mixed with the solid filtered from the solution. Often this is of little or no concern, but if its presence seriously contaminates the solid product some care must be taken in selecting the right filter aid. This fact may prevent the use of an aid, regardless of how badly the filtering operation might require assistance.

It is interesting in this connection that several activated charcoals and earths used for decolorizing or deodorizing may also be excellent filter aids and may thus perform a dual purpose when introduced into a liquid.

Gravity Filters

For a gravity filter to function at all, the filtering medium must permit the liquid to pass with a minimum of resistance. For this reason continuous gravity filters are limited to very free-flowing materials, both solids and liquid. Even intermittent filters are not particularly suitable for handling anything which is difficult to filter except in very small quantities or when the solid is present in very dilute suspension.

Since gravity sand filters are so widely used in the filtration

of domestic water supplies they are perhaps the best known of all filters, at least to the general public. There are several other types of gravity filters in industrial use which are highly important.

Intermittent Gravity Filters. The simplest of all gravity filters is the filter paper in a funnel. While there is no industrial counterpart of this filter, the funnel itself in larger sizes is often used for small scale filtrations in the manufacture of limited amounts of fine chemicals.

The *sand gravity filter* is the most widely used one of this class in spite of the fact that it is intermittent in operation, and that, in its operation, the solid material present in the liquid is first mixed with fine sand and then usually run to the sewer. Properly operated sand filters will give a crystal clear effluent, and have a high capacity through-put with a minimum of operational expense.

Sand filters have been used for decades both for industrial and domestic filtration. They have not, in that period, changed appreciably in basic design. Two general types of gravity sand filters are in use. One—the backwash filter—is by far the more popular. It consists of a heavy gravel base supported on a false bottom in an open tank. On top of the gravel layers are layers of successively smaller particles culminating with a fine sand layer at the top. The full depth of the filtering bed varies considerably from one installation to another, but thicknesses of six feet or more are quite common. An overflow trough or box at the top of the filter above the bed of sand, a distributor for liquid flowing to the filter, and proper valves to regulate direction of flow of liquid through the filter complete the installation.

The solid deposited in and on the uppermost layer of sand is really the filtering medium, so the filter usually must be operated for a few minutes with the filtrate going back to the raw liquor storage before it starts to run free of suspended solids. After a time filtration slows down because of the deposit of solids. When the filtration rate has decreased to a predetermined level, the filter is shut off, and is cleaned of deposited solid by passing the clarified solution or clean water upward through the filter bed. The deposited solids are lifted off the bed and floated out the

discharge trough. It is not uncommon for as much as ten per cent of the water filtered in one of these filters to be reused for back washing the filter.

The second type of intermittent sand filter more or less imitates natural conditions, in that filtration progresses slowly in huge outdoor basins. These filters are sometimes used for filtering water supplies, but are more often used for clarifying waste waters before they are discharged into streams. When the filter has clogged, a second unit is placed in operation, the first being allowed to dry. The solids are then removed by mechanical scrapers, and fresh sand spread to prepare the filter for reuse. This filter, like the others, is built up of layers of coarse to fine sand, the top layers being somewhat coarser where waste water is being clarified.

Continuous Gravity Filters. The continuous type of gravity filter may take any one of several forms, all having some means of continuously removing the solids which have collected on the filtering surface. Two general types of continuous gravity filters are in use, those having screens, or on rare occasions, cloth for a filter medium, and again, the sand filters.

Screen-surfaced gravity filters are built in many styles, with numerous modifications of each style available for special application. Both stationary and movable screens are used. They may be horizontal, vertical, or inclined, and either curved or flat. The moving screens may be shaking, traveling or rotary. The solids may be removed by gravity, by shaking, by mechanical scrapers, or drags, or by water showers or jets.

Inclined or curved *trash screens* are frequently employed in many industries as protective devices for removing accidental coarse particles from fluid streams. These consist simply of a bar grating or a punched-plate surface inserted in the stream of flowing water, and a scraper or drag to free the surface of trash as it is collected. The trash is drawn over the upper edge of the screen into a collection trough.

If the inclined grating is replaced by a continuous inclined combination flight and perforated plate apron conveyor, a *self-cleaning screen* is obtained. Trash is frequently removed from such a screen by passing it under a high pressure water shower or air blast just as it turns around the end roller.

Movable horizontal screens will separate a finer material from the water stream than will the inclined type of grating, and can be arranged to give a somewhat drier screened product. Rotating gravity screens are also widely used, being particularly useful where space is at a premium.

In those cases in which it is desired to have crystal-clear effluent, and where the sediment is too heavy to use an ordinary intermittent sand filter effectively, a *continuous sand filter* may serve the purpose. Due to the general difficulties of operation of these filters, however, it is often more desirable to operate an ordinary thickener, and clarify the effluent from this by means of a battery of intermittent sand filters.

One style of continuous sand filter in outward appearance resembles a small thickener. In the bottom of the tank, however, there is a standard sand filter with the scraper arm of the thickener set to just clear the sand surface and move deposited solids off the surface and into the discharge. If the sand tends to clog, surface layers can be swept off by slightly lowering the drag.

The second style of continuous sand filter is a large rectangular filter provided with partitions which, extending to the top of the sand surface, divide the filter into a row of long narrow beds, any one of which can be removed from operation at will. By shutting off the one strip and lowering a bell over it, it can be backwashed without interrupting the flow through other sections of the filter.

Vacuum Filters

In those cases in which the liquid cannot be passed readily through the surfaces of a gravity filter, where the deposited solids materially retard flow, where a fairly dry solid is desired at the filter discharge, or where washing of the precipitate is a required operation, the vacuum filter, with its ability to provide substantial pressure differences, may offer a very satisfactory solution to the problem of filtration.

Intermittent Vacuum Filters. Except for handling small quantities and the possibility of providing much longer periods for washing the precipitate, there is little object in operating an industrial vacuum filter intermittently. The labor require-

ment is likely to be many times higher per unit of material filtered than it is for continuous filtration, and the capacity per unit of filtering area and floor space may be much lower. However, it is sometimes quite important to free a heavy sludge of all of its entrained liquid, and if that liquid is likely to be viscous, as for example, sugar syrup, an extended wash may be essential to remove the liquid. In this case, the intermittent vacuum filter has a definite application.

The *leaf filter* is the basic design of all intermittent industrial vacuum filters. The filtering leaf is usually a hollow pancake-shaped frame over which the filter medium is stretched. The leaf is immersed in the suspension, a vacuum applied to the inside, and the precipitate is collected on the outside surface. The filtrate passes through and into a receiving tank. The filter cake builds up until the filtering rate slows appreciably. The filter is then transferred from the slurry tank to a wash tank. Wash is drawn through the cake as long as the vacuum is applied. The washed precipitate is removed by applying a slight pressure to the inside of the leaf. Commercial filters usually have a number of filter leaves attached to a common header.

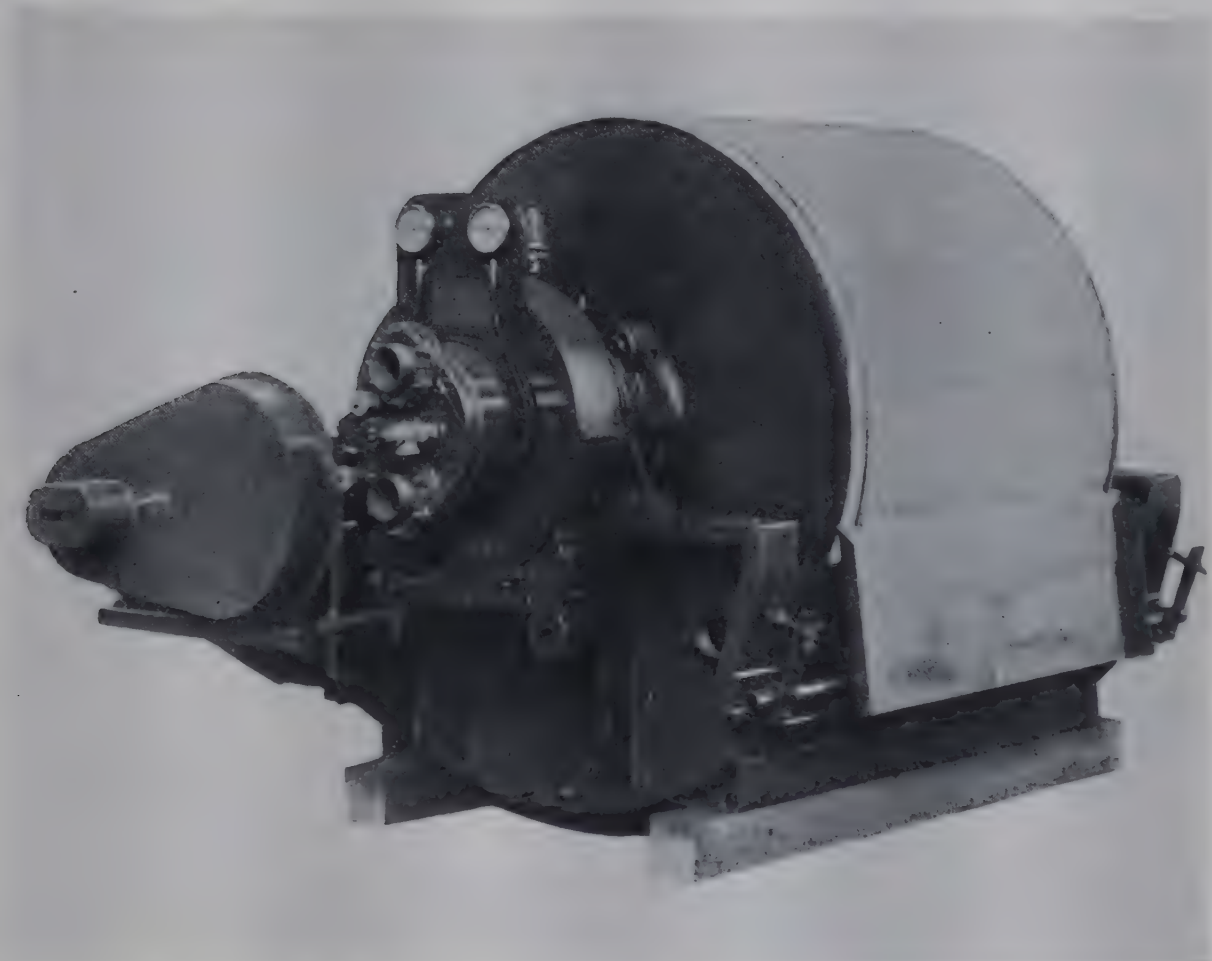
While seldom used industrially, the large Büchner funnel and the stoneware vacuum filter are very satisfactory for very small scale manufacturing.

Continuous Vacuum Filters. The continuous vacuum filter in its various designs is used in a veritable multitude of filtering operations, effectively handling slurries from less than 0.1 per cent solids to those so thick with suspended solids that they will barely flow. Almost every possible kind of low viscosity suspending liquid and all types of suspended solids can be handled in these filters. The stalwart of this group of equipment is the Oliver filter, with many others, notably the American (rotating disk filter), and the Dorr (internal drum filter), crowding it in general importance, and surpassing it in some types of filtering operations.

The *Oliver filter* consists of a horizontal drum, covered on its curved surface by a filter medium, and divided internally into a number of radial sections. These sections are arranged, through end plate manifolds and a rotary sliding valve, to be connected

with one or more vacuum systems through part of each revolution, and finally to a pressure system for a very few degrees of movement.

In operation, the drum is immersed in a tub which is kept filled with the liquid to be filtered. Agitators in the cylindrically



(*Oliver United Filters, Inc.*)

Figure 86. Vacuum Filter. Oliver Rotating Drum.

shaped tub assure that the solids will reach the filtering surface. The solids build up on the section of the drum which is immersed and on those particular segments connected with the first vacuum section. Vacuum applied after the coated segment emerges from the suspension in the vat tends to dry the filter cake. This may or may not be necessary. As the segment slowly rotates with the drum, the cake deposited on its curved surface may be washed and dried through an arrangement of shower pipes and other vacuum systems.

The air blast near the end of the cycle lifts the filter cake

from the surface so it can be trimmed off the filter by a horizontal knife-edge (doctor blade) set to just clear the filtering surface.

Except for the difference in design of the filtering surface, the other filters of this group all operate in a similar manner.

Several flat-surface, continuous filters are also manufactured. One type consists of an endless wire or cloth belt which is carried over and in close contact with stationary suction boxes. The general arrangement of the belt resembles a rather broad and short length belt conveyor. A large rubber belt or other movable or stationary dam keeps the liquid from flowing over the side of the filtering surface. A continuous rotating horizontal disk filter is also available.

Pressure Filters

In those problems of filtration in which it is necessary to remove a difficultly-filterable solid from suspension without the use of a filter aid, or to filter a suspended solid from a fairly viscous liquid, it is necessary to apply higher pressures than can be obtained by either gravity or vacuum filters in order to force the liquid through the filter medium. Pressure filters have been introduced to meet this need.

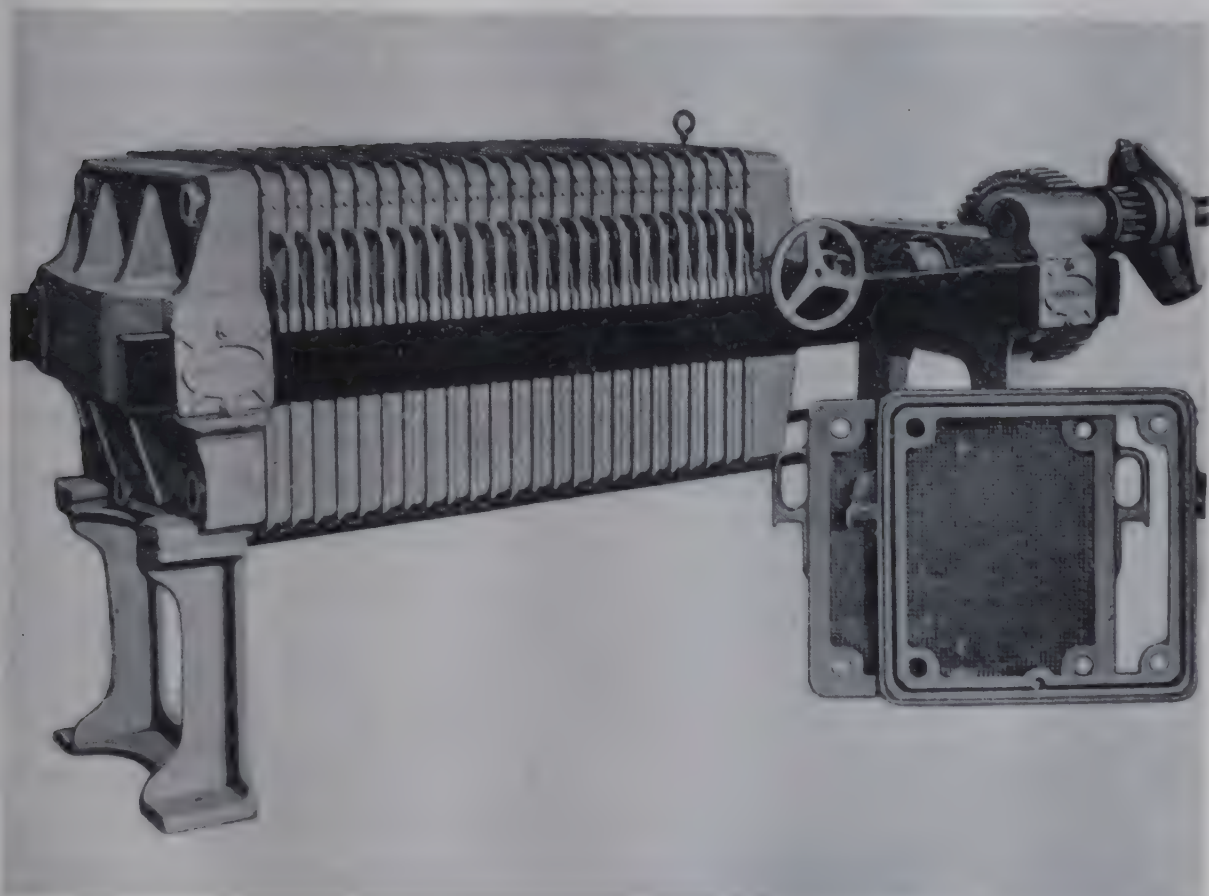
The slurry may be pressure-fed to the filter surface by means of liquid pumps or pressurized blow cases; the latter method is favored because the slurries are frequently granular and highly erosive to pump surfaces.

Positive-pressure Filters. There are several types of pressure filters, with one, the filter press, more or less dominating the field. However, several other types enjoy great popularity in particular industries.

The *filter press*, as a plate-and-frame filter, or the quite similar form, the plate filter, is itself made in a number of different styles to permit some variations in operation. They all follow a similar basic pattern, however. The plate-and-frame filter consists of a series of plates and frames between which the filtering medium is stretched. A pair of heavy channels for supporting the plates and frames and a mechanical or hydraulic ram for tightly closing the assembly completes the unit.

The plates are solid metal leaves having their faces corrugated

in various designs to allow liquid to pass between the filtering medium and the face of the plate. Near the top corners are holes which match one another when the press is assembled and provide channels for the admission of slurry and wash water. Similar holes at the bottom corners communicate with the channels on the face of the plate and provide filtrate outlets. Various hole



(T. Shriver & Company, Inc.)

Figure 87. Filter Press. Plate and Frame Type.
Closed delivery; mechanical closure.

and communication arrangements are possible. The frames are open. Their rims are drilled to continue the corner channels of the plates. The frames hold the plates a short distance apart and thereby provide a space between them to receive the solid filter cake.

The plate presses are quite similar except that the frames are eliminated, and the plates are more deeply dished to provide cavities between them for the cake. Feed is usually through the center.

Filter presses may be supplied with hollow steam heated

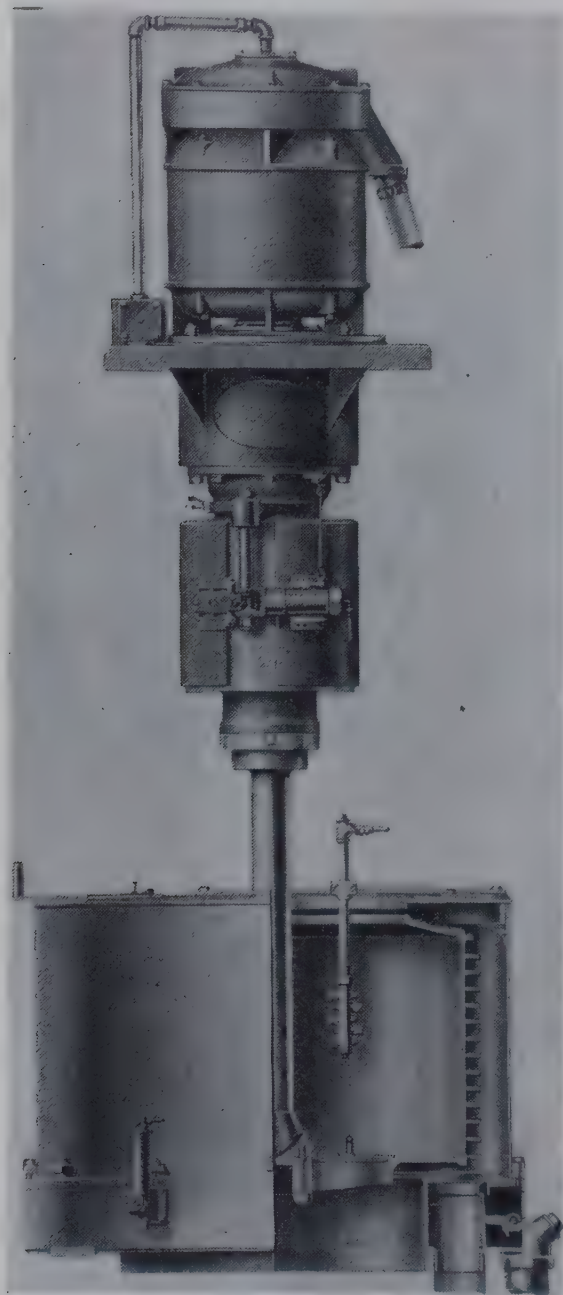
plates, with various arrangements for convenient operation, and sometimes with means of removing the solid without dismantling the press.

The labor required for the operation of filter presses is very high. Some direct-pressure filters are arranged to reduce this

labor requirement. It is claimed that some of the other types of presses are cleaner to operate.

Several types of industrial pressure filters contain a cylinder into which the slurry can be pumped under pressure. Filtering is done on filter units not greatly different in construction and appearance from the leaf type vacuum filters. The cylinders in most cases are horizontal. The Kelly, Sweetland, Vallez and other filters are of this class.

The pressure filters as a class, compared to vacuum filters, require much more labor for operation and are likely to be very messy pieces of equipment as far as "housekeeping" is concerned. They do, however, have several distinct advantages, including such features as the ability to handle heavy-bodied liquids, provide a washing period as long as desired, and allow the use of volatile solvents, and can, if necessary, use the paper filter media which are so useful for various clarification filtrations.



(Western States Machine Co.)

Figure 88. Centrifuge. Suspended Basket Type.

Only a few of many filters have been described in this section on pressure filters. For example there are the streamline or edge filters, the cartridge filter containing cotton flannel labyrinths and used in filtering automobile lubricating oil, pipe-line

strainers, the Sparkler filter used widely for clarifying beverages and syrups, and many others.

Centrifugal Force Filters. The ordinary *basket centrifuge*, lined with a fine mesh wire screen or a fabric filter cloth, is an effective filter for slurries of reasonably free-filtering crystals in a heavy, viscous liquid. The basket centrifuge consists of a perforated drum suspended on a vertical shaft which can be turned at a high rate of speed. The solids are caught on the inside walls of the drum and are removed by plows when the centrifuge is stopped. Several continuous centrifuges are arranged to remove continuously the solid which accumulates on the interior of the rotating element.

Dialysis

Colloidal materials resist most ordinary efforts to effect their separation from the liquid in which they are dispersed. If it is a solution which is to be recovered from the colloidal suspension, it is sometimes possible to remove this solution by replacing it with water by the process of dialysis through a membrane. Even high molecular weight solids or liquids in solution may be left behind, while smaller molecules pass through the pores of the membrane. If the solution containing the colloidal particles is placed on one side of the dialyzing membrane and water placed on the other, the solution will be reduced in concentration by passing through the membrane, water coming in to replace it. The colloidal particles are left in the diluted solutions.

This process has little industrial application. It is used to some extent to recover sodium hydroxide from spent caustic liquors used in preparing viscose (rayon). The leaching operation to produce beet sugar is one of dialysis, the cell wall acting as the membrane to prevent the passage of colloidal materials.

Techniques Based on the Electrostatic Properties of the Solid in Suspension. Some solids, such as clays in suspension, will migrate to one pole or the other when placed between electrodes to which a direct current is applied. This phenomenon of solids moving toward an electrode is known as cataphoresis, and the principle is the basis of the design of at least one machine made for dewatering clays.

Techniques for the Single Step Reduction of a Solution or Slurry to a Dry Solid. It is often necessary to produce a dry solid product from a solid in solution or suspension. The normal procedure is to reduce first from a solid in solution to a solid in suspension, reduce this by one of the many methods to a damp but solid mass, and complete the process by applying one of the methods, usually drying by heat, to remove the last of the remaining liquid.

Some heat-sensitive materials are not receptive to this treatment, and because they are colloidal to start with (skim milk for example), could not be concentrated effectively by settling, filtration, or any of the other usual methods. These materials can frequently be reduced from either a dilute solution or a thick suspension to a dry solid in a single step, and although separation is secured by application of heat, it may sometimes be done at such high vacuum and low temperature, or at such great speed that deterioration of the solid in the process is minimized.

The techniques for separation fall into two distinct classes: those performed at substantially atmospheric pressure, and those carried out at medium or high vacua. The equipment for these two processes is quite similar in design. That used for vacuum operation requires the addition of a pressure-tight housing, a means for removing the finished solid without breaking the vacuum, and auxiliary equipment for producing and holding the required vacuum.

Two general types of equipment are used for drying liquids to a dry solid product. These are drum dryers, in which drying may require 30 to 40 seconds, depending upon the speed of the drum; and spray dryers, in which liquid suspensions or solutions may be reduced to dry residues in less than 5 seconds.

The *drum dryers* are simply large, rotating, horizontal steam-heated drums which collect a layer of paste or solution on their curved surface as they dip into a vat containing the material, or as liquid is sprayed on their surface. A doctor blade removes the dried solid before the drum is recoated.

Spray dryers have many advantages, the outstanding one being the extreme rapidity with which drying can be accomplished. Materials as heat-sensitive as bananas have been pulped and dried

to a powder in spray dryers without damage to the dried product. A spray drier is essentially a large closed tank or chamber into which heated gas and atomized liquid can be brought together. Vaporization from the tiny droplets of liquid is virtually instantaneous, and only vapor and dust leave the equipment. A dust and gas separator; fans to secure adequate circulation and

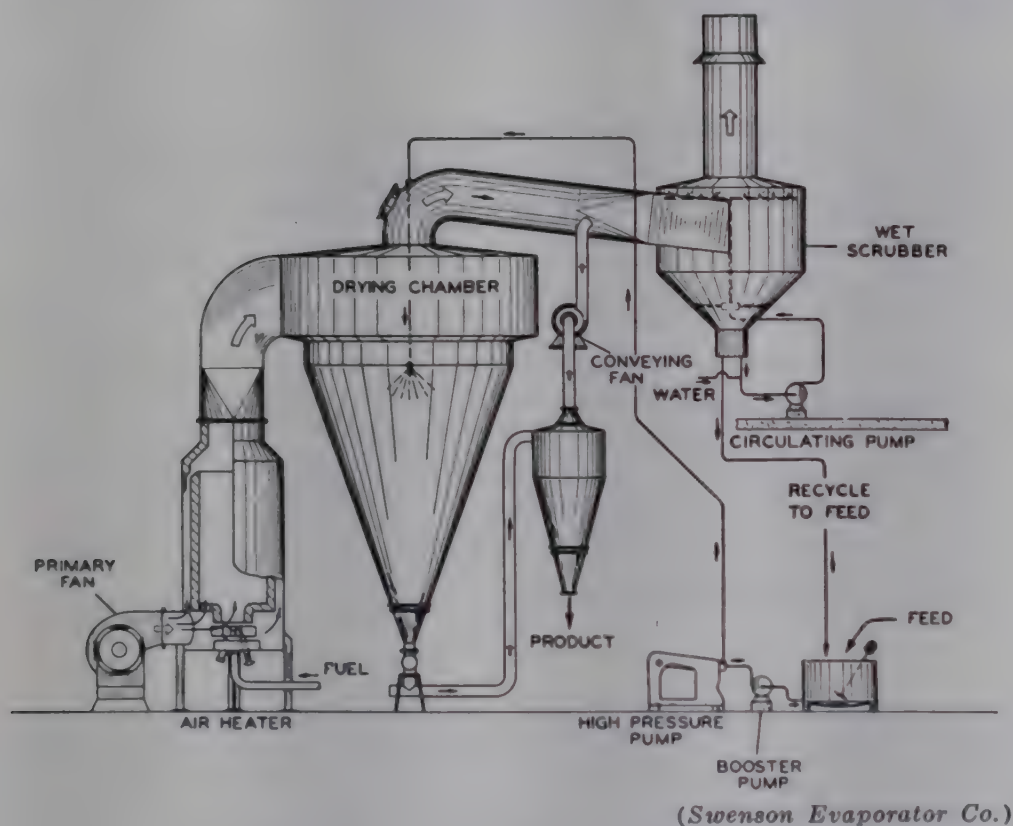


Figure 89. Spray Dryer Assembly.

movement of gas, liquid droplets, vapor, and dust; a source of heat for warming the gas stream; and pumps and atomizers for dispersing the liquid complete the installation.

Another reference to the technique of freeze drying is appropriate in this section, since through this operation dehydrated citrus juices and dried pharmaceuticals have been prepared in a quality impossible of attainment with any other method of drying. Freeze-drying techniques are a result of the successful development of large-capacity high-vacuum pumps and of the refrigerated moisture trap.

18 : SEPARATION OF A LIQUID FROM A LIQUID

Techniques for Separating Liquids from Liquids

Techniques for separating two liquids insoluble in each other

Separation of liquids having no interfering features

Slime removal

Handling of emulsions

Techniques for separating liquids in solution

Based on relative vapor pressures

Based on change of solubility with change in temperature

Based on relative solubility in a third liquid

Based on solubility changes induced by adding a third substance

Based on relative freezing points

Based on adsorptive properties of solids toward certain liquids

Based on chemical properties

Many large industries today owe their existence to successful, efficient, and low-cost methods which have been developed for the separation of one liquid in reasonably pure form from a mixture of two or more liquids. The production of motor fuel from crude oil is an excellent example of this separation. There are many others basically important to industry.

The factors which should be considered in the selection of a technique for the separation of one liquid from another are:

1. The physical properties of the two liquids
 - a. Mutual solubility
 - b. Solubility in other liquids
 - c. Tendency to be adsorbed on a solid
 - d. Vapor pressure
 - e. Density
 - f. Viscosity
 - g. Melting point
 - h. Heat sensitivity

2. Initial condition of the liquid mass
3. Amounts of material to be handled
4. Toxicity, flammability, or other hazardous properties of liquids
5. Degree of separation required
6. Value of material being handled
7. Corrosive properties of liquid and possible need of corrosion resistant equipment.

TECHNIQUES FOR SEPARATING LIQUIDS FROM LIQUIDS

Techniques for the separation of two or more liquids may be roughly classified in two groups: (1) those for the separation of two completely immiscible liquids, and (2) those for the separation of liquids which are miscible in all proportions. If the properties of a liquid mixture place it at some position between these two extreme conditions, it must usually be treated by methods applicable to members of the second group.

Techniques for Separating Two Liquids Insoluble in Each Other

Liquids insoluble in each other can normally be easily separated by taking advantage of differences in density. If no difference in density exists at normal temperatures—which, incidentally, would be unusual—the two liquids will almost always have different density-temperature relationships, and differences in density may be induced by changing the temperature of the mixture.

Slimes or sludges which are sometimes present make separation difficult or impossible, and in these cases separation must often be preceded by filtration or other treatment to clarify the liquids.

It is very difficult to separate two immiscible liquids which are in the form of a semi-permanent or permanent emulsion of one liquid in the other. Once the emulsion is broken, however, the separation is usually quite simple.

Separation of Liquids Having No Interfering Features.

Gravity Separation. If the difference in density of two liquids is appreciable, and if the droplets of the liquid in suspension are not so fine as to be colloidal, the two liquids will usually settle into

two distinct layers if left quiescent in a tank or other vessel for a reasonable time. Industrial procedures, except for amounts handled, are not appreciably different from the use of the separatory funnel in the laboratory.

By the use of a tank having a conical bottom, accurate separation of two liquids can be obtained, the heavier liquid being drained from the bottom. However, since sight glasses on tanks become coated and opaque and are usually very laborious to clean, this method of separation, which requires the reading of liquid interface levels, is attended by considerable difficulties. Often, therefore, the lighter liquid is siphoned from the top layer. This procedure also tends to give a cleaner light liquid than when both heavy and light liquids are withdrawn through the bottom. The main disadvantages of this operation are that the siphon pipe cannot remove all the top layer, and that there may be some difficulty in manually lowering it to exactly the right level just above the interface between the liquid layers.

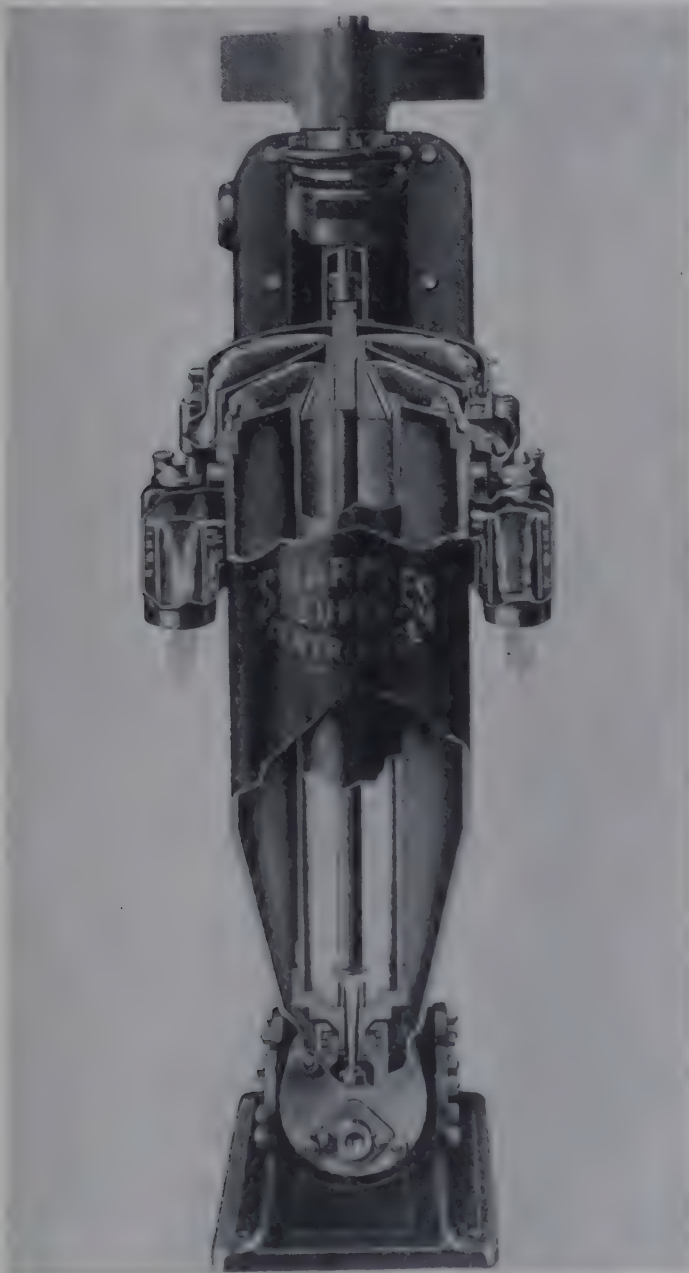
The solution to the first difficulty may sometimes be secured by partially draining the separation tank and allowing the liquid close to the interface, both above and below it, to remain in the tank and be mixed with the next charge.

The second problem may be solved if there is sufficient difference in the density of the two solutions to suspend a float between them. By anchoring the intake end of the siphon pipe to a float light enough to float on the more dense liquid but heavy enough to sink in the lighter layer, the siphon will follow the interface. An interface float can also be used to good advantage to control drain valves or to sound alarms where separation is to be carried out by drainage through a bottom outlet and where color of the liquid or coating on the sight glasses rules out visual observation of the location of the interface.

Centrifugal Separation. Except in handling very easily settling liquids and those in which the interface is clear and sharp, the gravity separation is definitely of less industrial interest than is mechanical centrifugation. In the modern industrial centrifuge separation is rapid and accurate, and except for mechanical failure and the necessity for occasional cleaning, is continuous. Therefore, it has many advantages. Centrifugal separators rapidly

pay for themselves in almost any separation of two immiscible liquids.

The *centrifugal separator* usually consists of a stack of inverted cones which are rotated in and with a rotating bowl. The liquid is



(The Sharples Corp.)

Figure 90. Industrial Separator. Super-centrifuge (Sectionalized view).

fed to the bowl, where it is given high rotational speed. The lighter liquid proceeds toward the center to be discharged through an adjustable opening near the center, and the heavier liquid is removed through another opening near the perimeter. This machine is in reality a concentrator, because if it is fed with a liquid

of uniform density it will discharge liquid to both light and heavy liquid outlets.

The liquid-liquid centrifuge is also provided with special bowls and cones to give a true separation. In this machine, component concentrations varying from almost pure materials at either end can be separated without much danger of breakover of one component into the discharge of the other.

For handling liquids which are extremely difficult to separate, a super-centrifuge has been developed. This is a high-speed machine having a small diameter bowl and spindle.

Separation by gas flotation. A rather recent innovation of somewhat limited application in the separation of two liquids in suspension in one other is to use gas bubbles as a gathering medium. In this technique the liquids in suspension are blown with an inert gas, the liquid having affinity for the gas being caught by the bubbles and gathered in the froth. The operation closely resembles froth flotation for the separation of solids.

Slime Removal. Where slimes, scums, and deposits of solids or semi-solids occur, as they often do in liquid systems, the problems of separation by gravity or by centrifugation may be greatly complicated. The actual interference can be determined only by experimentation. If the difficulty is purely mechanical, the use of settling tanks designed to permit sides and bottom to be scraped by mechanical scrapers, and the use of valves and drains which can be cleared by push rods may be all that is required. If the deposits interfere with the formation of a distinct interface, it may be necessary to treat the liquids centrifugally to effect a separation. Slimes may be so troublesome that before either settling or centrifugation of the liquids it may be necessary to remove the solids by one of the methods for separating solids from liquids.

Treatment of Emulsions. Emulsified liquids often present extremely complicated problems of separation, resisting direct separation almost completely, and often causing some difficulty if subjected to the usual methods for separating liquids in solution. The liquid droplets in an emulsion frequently can be coagulated, or the stability of the emulsion can be decreased so that it can be separated successfully in the high-speed centrifuge.

Various techniques for breaking emulsions are available; they meet with varying degrees of success in different liquid systems. The application of heat gives the most satisfactory results in the greatest number of cases of emulsion breaking. Occasionally, merely raising the temperature enough to lower the viscosity will be sufficient to break an emulsion. Heating to a point where films may be broken by partial vaporization, but to temperatures well below the boiling point of the liquid may give excellent results. Where lower temperatures are not effective, coagulation may sometimes be obtained by digesting the emulsion under either atmospheric or elevated pressures.

Some emulsions which are not broken by heating or cooking may sometimes be broken by freezing; others may respond to the addition of salts or of acids which may neutralize the electric charge which holds colloidal particles in suspension. Emulsions can sometimes be separated by weighting procedures similar to those used for separating colloidal solid particles, or by adsorption in coarse materials such as diatomaceous earth.

Broken emulsions will respond to ordinary settling or centrifugal treatment.

Techniques for Separating Liquids in Solution

Any one of three requirements may prevail in the removal of a liquid from a liquid: (1) the necessity for the separation into two pure liquids; (2) the need for partial removal of one pure liquid leaving an impure residue of the second; and (3) necessity for the separation into two impure liquids. The prevailing situation is the dominant factor in selecting the technique to be employed, although similar procedures often will produce quite different results if carried to only partial completion or if conducted under only slightly different conditions.

The properties of the two or more liquids upon which techniques for their separation are based are as follows:

1. Relative vapor pressures and relative vapor pressure-temperature relationships
2. Variation of relative solubility with temperative changes
3. Relative solubility in another liquid

4. Solubility changes created by dissolving a solid or a liquid in the system
5. Freezing points
6. Relative degrees of adsorption on a solid adsorbent
7. Chemical properties

Techniques Based on Relative Vapor Pressures. Two groups of techniques, i.e., evaporation and distillation, are probably two of the most extensively studied unit operations in the whole field of chemical engineering practice. Both are designed to separate liquids from a solution and both are based on the relative vapor pressure of the two liquids. The distinction between the two groups lies in the spread between the vapor pressures. Evaporation deals with the separation of liquids of relatively high vapor pressure from those of low vapor pressure. Distillation, on the other hand, relates to the separation of materials of quite similar vapor pressures.

Evaporation

The process of evaporation, as practiced for the purpose of removing water from a solution of a salt or other solid or liquid of low vapor pressure in water, is one of the oldest of all industrial techniques. It has already been described to some extent in connection with the removal of solids from a solution in water, but it is most appropriate that it be discussed again at this point.

The methods of evaporation and the equipment used to carry them out do not differ in any particular regardless of whether the evaporative process is being used to separate water from a nonvolatile liquid like glycerin, or to remove water from a solution of a salt in water so as to concentrate the solution in preparation for subsequent crystallization. Solvents other than water are also removed from nonvolatile residues by evaporation. However, water is so preponderantly the volatile liquid which is removed that it is the solvent usually considered in this respect. Any evaporator equipped for recovering the vapor in an uncontaminated form is suitable for vaporizing solvents other than water.

To review briefly, evaporation may be carried out by (1) direct heat transmitted by radiation in solar evaporators; (2) direct heat

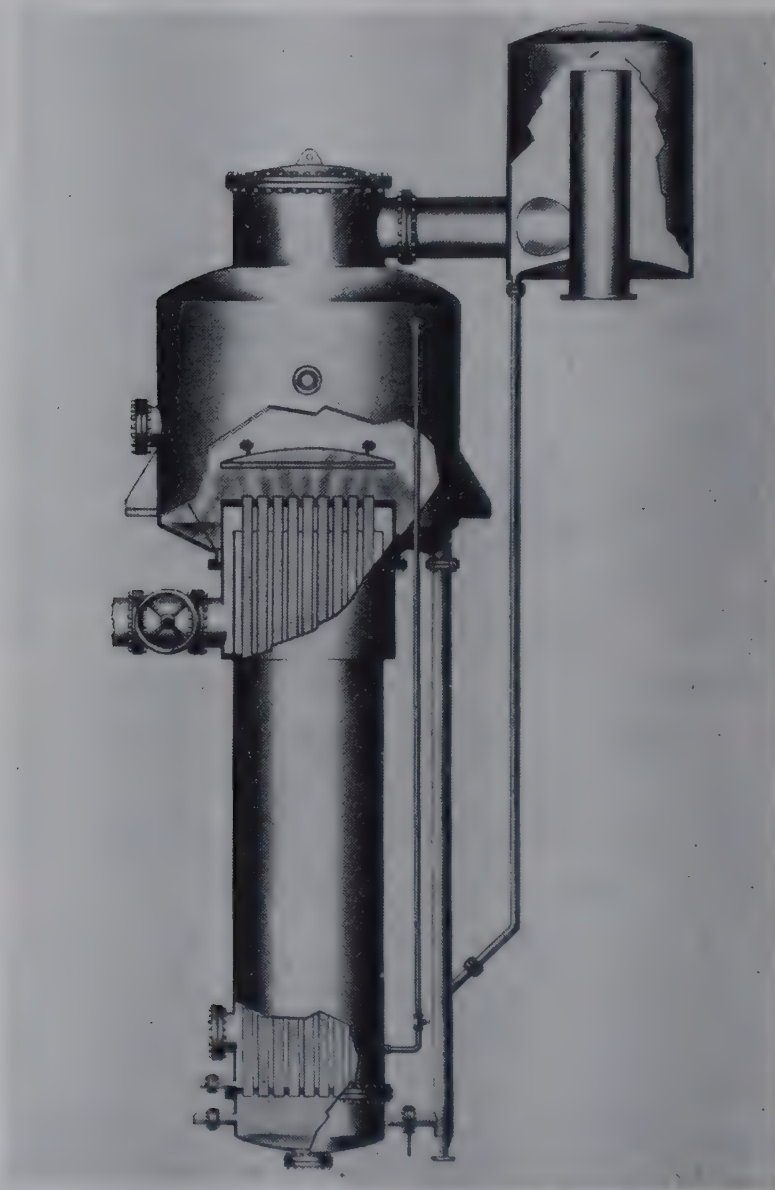
transmitted by a heated gas to the liquid being evaporated in spray evaporators and dryers, packed towers, and other types of gas-liquid mixers; or (3) indirect heat transferred through surfaces to the liquid held in either open or closed vessels.

Direct-heat evaporation is extremely important for both separation and concentration procedures. A number of types of equipment make satisfactory direct-heat concentrators. Spray evaporators, packed, wetted wall, cascade and plate towers, are all eminently suitable for the purpose. Other types of equipment such as the disk evaporator have also been developed for the specific purpose of direct-heat evaporation. Heat-transfer coefficients are at a maximum in the direct-heat evaporator. Evaporation is rapid and not often subjected to the many difficulties which plague the operators of indirectly heated evaporators. However, air, other gases, or products of combustion must be brought into contact with the material being evaporated, thus opening the possibility of deterioration or contamination of the residues. Further, vapors of the liquid being evaporated are mixed with large volumes of inert gas and thus are expensive to recover. Although direct-heat evaporation often is carried out at temperatures well below the boiling point of the solution, it becomes very inefficient at such low temperature levels. Finally, heat contained in vapors is immediately lost in direct-heat processes.

Direct-heat evaporation, without the necessity of introducing heat in large volumes of gas, can be achieved by the use of radiant heaters or of infrared lamps. Such lamps have become quite important as a means for drying industrial finishes where rapid evaporation is required, where the heat should be concentrated on the surfaces, and where it is essential to recover the solvent vapors from the drying coating. The range of applicability of this method of evaporation to more strictly chemical processes has only begun to be appreciated. The major disadvantage is the cost, since the heat is supplied by electric power. Any fog or coating settling on and adhering to the surface of the lamps sharply reduces their efficiency. The use of open radiant coils is possible, although not often of any importance for evaporation.

Evaporation in open pans, although carried out on a fairly large scale in the salt and other industries, is best suited for very small operations, where the amount of evaporation required does

not justify the installation of the more expensive closed vessels. Exceptions to this rule are found in those instances where the boiling point rise is so great that more than one effect could not be used in any case, and where evaporative temperatures are so



(Goslin-Birmingham Co.)

Figure 91. Long Tube Evaporator; Natural circulation (Sectionalized view).

high that direct heat from oil or gas flames on the outside of the container is necessary in order for the liquid to reach the required temperatures. Consequently, in spite of its inefficient use of heat, open-pan evaporation is often employed industrially and probably will continue to be for some time to come.

A closed vessel for indirect-heat evaporation has several advantages. For example, the pressure can be controlled within the vessel, and therefore, temperatures well below the normal boiling

point of the solvent can be used. Another advantage is that the solvent, and what is more important in many cases, the heat in the solvent, can be salvaged in almost quantitative amounts.

The *vacuum evaporator* may be used singly to reduce the temperature of vaporization, or used in series to conserve heat. It is constructed in a number of different styles depending on the service in which it is to be used. The major distinction in the older evaporators is between those having vertical or horizontal heating units, and in newer installations between those in which outside heaters with circulating systems are used and those heated by internal heaters.

Several problems are often encountered in the operation of evaporators. One of these is the tendency to form large volumes of spray, and another to form copious quantities of foam. Virtually all evaporators have a large vapor space to minimize these difficulties. Foaming is sometimes reduced by bringing the foam into contact with heated surfaces. To accomplish this, a liquid may be carried below its normal level just to expose tubes above it to act as foam breakers. Other methods for reducing foaming, such as the control of the pH of the solution or the addition of kerosene or other foam breakers, are sometimes effective. All modern evaporators are built with spray separators such as baffle plates, cyclones, or other such devices near the vapor outlet of the evaporators.

The problem of heat transfer becomes very serious when highly viscous solutions are evaporated at temperatures not much above atmospheric. The introduction of outside circulation through low-head high-volume pumps has been a great help in handling these materials, and many modern evaporators are of this design.

Several evaporators arranged in series, with all but the first body being heated by vapor from the evaporator preceding it in the series, is a *multiple-effect evaporator* system. The actual energy lost when steam converts liquid to a vapor while it itself is condensed is only a small fraction of the heat effects involved in vaporization. Hence, most of the energy of the steam can be recovered in the vapor. Since each evaporation in the series must be carried out at a lower temperature than the one before it, and because boiling point rise caused by dissolved substances and by hydrostatic head reduces the apparent drop of temperature, prac-

tical considerations limit evaporator series, under the best conditions, to about seven effects.

Another type of evaporating apparatus, which is of unusual interest because of its large capacity for its size, is the *vapor-recompression evaporator*. Vapor, as it leaves an evaporator, differs from the steam in the chest only because it is at a lower pressure and lower temperature, and therefore has a slightly lower energy content. Some energy is actually consumed in the process. This energy can be replaced and the temperature of the vapor raised to that of the original steam by passing the vapor through a power-driven compressor. The compressed steam is reused in the steam chest. The only steam make-up required is that necessary to heat the raw solution to the boiling point.

This evaporator, simple and efficient as it is, cannot compete economically with a multiple-effect steam-vapor unit, unless it is being operated at a location where electric power is very cheap and fuel very expensive. Its compact nature, however, makes it very useful for treating water supplies in remote localities. Many of these units were built for the Armed Services during the last war.

Vapor distillation, a technique which has been mentioned in an earlier chapter, should be considered briefly as a type of evaporation. Although not quite as important as it once was because of improvements in high vacuum techniques, it is still quite important in some industries as a means of vaporizing volatile materials which have high boiling points but are heat sensitive at temperatures much below their normal boiling points.

If vapor distillation is carried out under medium-to-high vacuum, vaporization of fairly high-boiling materials can be carried out at temperatures which differ little from atmospheric temperature.

The major objection to the use of steam distillation as a means of vaporizing many of these materials is the fantastically high heat consumption per unit of material vaporized.

Distillation

A mixture of two or more liquids, all of which have appreciable vapor pressures, can often be separated into its components or

concentrated in one component or the other by a process known as distillation. While it is theoretically possible in perfect distillation systems to obtain complete separation of substances and therefore produce pure products, this can be done only with an infinite number of separations. Hence complete separation of liquids by distillation is commercially impracticable.

Distillation is carried out commercially either as a batch process (differential distillation) similar to the conventional laboratory method, or as a continuous process (equilibrium distillation). The latter is the more important of the two methods.

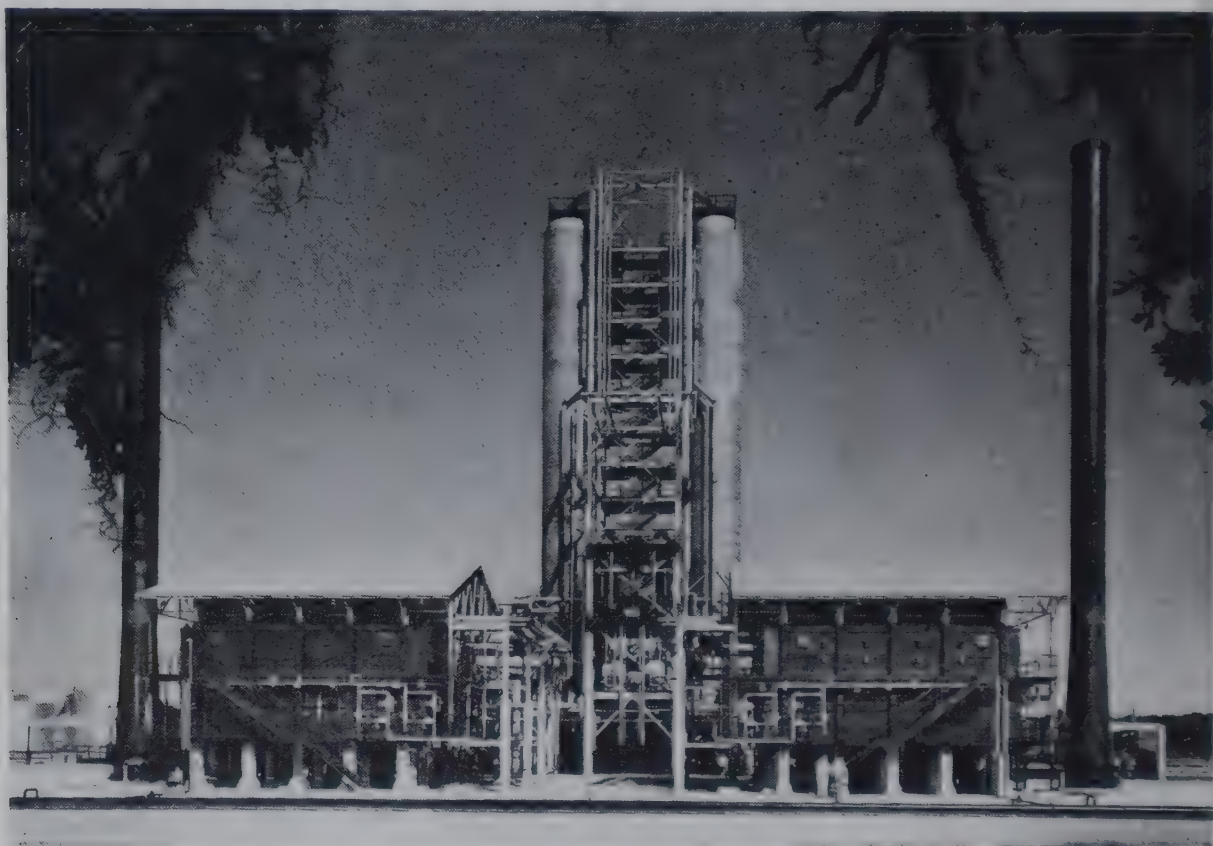
Batch Distillation. The techniques for batch distillation are those of the laboratory distilling flask and fractionating column enlarged to meet commercial production requirements. The commercial equipment consists of a steam- or flame-heated vessel having a vapor line connected to the base of a gas-liquid contacting tower of any one of the several designs. Packed towers, plate towers, and others are all suitable for the process. A vapor condenser connected to the top of the column completes the installation. Stills for handling easily separable liquids may often dispense with the fractionating column.

In batch distillation the product which is withdrawn varies continuously in composition, so it must be tested at regular intervals throughout the distillation and directed to different receiving tanks depending upon its composition and boiling point.

Continuous Distillation. The basic parts of continuous distillation equipment consist of a source of heat, a rectifying column, a reflux and product condenser, and the necessary pumps, controls, and storage tanks. The heat source may be a heat exchanger such as the tubular heater of the petroleum industry; or the heat may be supplied through coils in the bottom (reboiler) section of the column itself.

In the usual distillation technique, the liquid to be distilled is fed to some intermediate point in the column at a temperature below, at, or above its boiling point. The higher-boiling portion works its way down the column to the bottom section where it comes in contact with a heated steam chest in the so-called "reboiler" section. Here any low-boiling liquid is stripped out before the heavy fraction is discharged from the column. If only

two products are obtained—"overhead" and "bottoms"—the vapor is drawn from the top of the column and condensed in a heat exchanger. Part of the condensate is usually returned to the top of the column as reflux; the remainder is run continuously to product storage. If a still is fed continuously with a raw feed



(The Lummus Co.)

Figure 92. Petroleum Pipe Stills and Fractionating Towers.

of constant composition and at uniform temperature it may operate indefinitely without being shut down unless the column is fouled by decomposition products or sludge.

Other than the several methods of feeding and handling products, the major differences in stills concern the column itself. Any of the columns described for mixing gases and liquids, such as packed, cascade or any of the plate columns, are suitable for separations involving only two products. Only the plate-type column is satisfactory for producing more than two products.

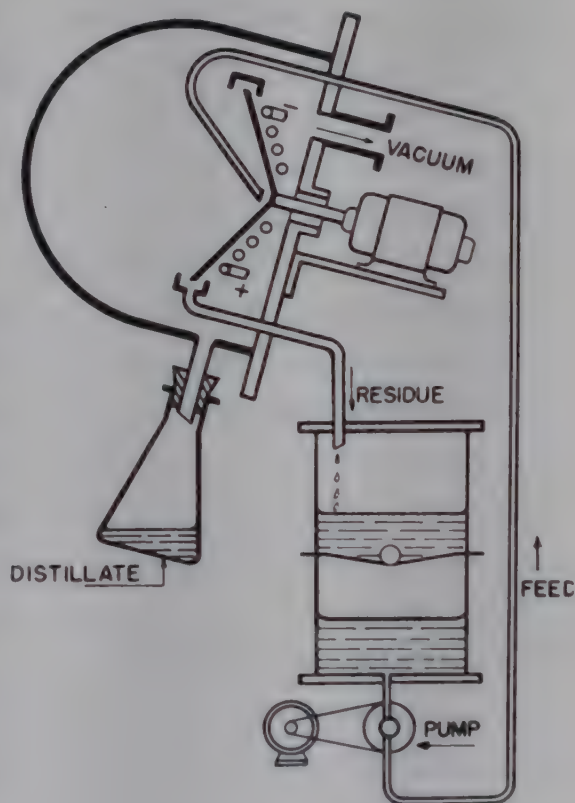
Other Distillation Techniques. Distillation progresses very easily if the materials are unaffected by the heat required to vaporize them, and if the liquids exhibit a "normal" vapor-

pressure relationship, that is, if the vapor evolved from any mixture of the two substances is richer in the lower-boiling component. Mixtures of liquids which fail to meet these requirements present problems which are difficult and sometimes almost impossible to solve.

Vacuum Distillation. Heat-sensitive substances can sometimes be handled safely at temperatures somewhat lower than their boiling points at atmospheric pressure. These substances can often be distilled successfully under vacuum, and vacuum distillation units are widely used for handling this type of material.

Molecular Distillation. A recent addition to the list of industrial techniques for distillation are the very high vacuum methods. Molecular distillation is the ultimate in this respect. In this process the vacuum is so high that the mean free path of molecules becomes comparatively long. The condenser is separated from the evaporator by a distance less than this mean free path.

Two molecular stills have been developed: the falling-film still, in which evaporation takes place on a warmed, inverted thimble, and condensation takes place on the inside of a closely surrounding glass cylinder, is one of them. The other, and the more important industrially, is the centrifugal still. In this unit, the liquid to be distilled is fed to a rotor where, by centrifugal force, it works its way up the rotor's slanting, heated walls. The more volatile component is distilled off, is collected on the internal condenser, runs to a collector at the bottom, and is withdrawn. The residual liquor passes up to the rim of the rotor where it is collected.



(Distillation Products Industries
Eastman Kodak Co.)

Figure 93. Molecular Still.
Centrifugal type.

Pressure Distillation. Many difficult problems in the separation of liquids are encountered in the treatment of liquid systems in which constant-boiling mixtures are formed. At this, the azeotropic composition of the mixture, the vapor evolved has the same composition as that of the liquid and obviously no separation by vaporization can take place.

The application of either pressure or vacuum may appreciably distort the vapor pressure-temperature curves. If this can be done, it is sometimes possible to shift the composition of the constant-boiling mixture enough so that distillation can progress to the desired point without crossing the new constant-boiling composition lines. In other cases, it may be possible to distill at one pressure, and then to finish the distillation by redistilling the overhead or bottoms at another pressure.

Azeotropic and Extractive Distillations. In addition to control of pressures, at least two other methods, quite similar to one another in general approach, have been found to be successful in the separation of many azeotropic mixtures. Both methods involve the addition of a third liquid to the system. If the new component itself forms azeotropic mixtures, usually minimum-boiling mixtures with one or both of the components in the original system, the resulting separation process is known as azeotropic distillation. If the addition agent is relatively nonvolatile compared to any of the liquids in the original mixture, the process is known as extractive distillation. Either azeotropic or extractive distillation can be conducted in ordinary distilling equipment, but special control is required in either case to provide proper operation of the unit. The details of operation are often empirical.

In comparative features, azeotropic distillation is preferred for batch distillation, and for those cases of continuous distillation where the overhead fraction is much smaller than the bottoms fraction. Extractive distillation is probably best for the average continuous distillation and shows considerable promise for much wider adoption than it now has.

Techniques Based on a Change of Solubility with a Change in Temperature. The phase relationships of a system of two liquids in solution may be such that when the temperature is changed, one or the other of the liquids may separate from the

solution or the two liquids may separate into relatively insoluble phases.

Techniques Based on Relative Solubility in a Third Liquid. Solvent-extraction techniques for the separation of two liquids in solution are gaining wide popularity because of the availability of cheap solvents and the great simplicity of the process. Probably the most valuable application of solvent-extraction techniques is to remove traces or relatively small quantities of one liquid from a fairly large body of other liquids. This is especially important if the liquid present in small quantity has the lower volatility.

Solvent-extraction methods are also extremely useful in solving problems of liquid separation in many cases where evaporation and distillation methods fail because of the high boiling points of the liquids, the heat sensitivity of the materials, or the failure of vapor pressures to provide adequate differences to promote separation. It is also useful in separating or pretreating mixtures containing one or more gummy substances which might make the liquid mixture difficult to handle in stills or evaporators. The relative facility of some solvent-extraction processes indicates that they may be practicable even where distillation or evaporation is entirely feasible.

A number of solvents have found wide application. Liquid propane, liquid sulfur dioxide, furfural, ketones, and many others have special solvent properties. Several materials exhibit a rather wide variation in solvent power at temperatures close to the critical, and this has been utilized in several new processes for solvent extraction.

The solvent extraction of a liquid may be accomplished by any technique providing single or repeated contacts of one liquid with another. Actually a number of quite different methods can be used to promote extraction. The liquid and solvent can be agitated together and run to a single settling chamber. The solvent may be added in small amounts with a settling and separation after each addition. Solvent may be added to the last of a series of mixers and settling tanks, extract from each tank moving to the mixer ahead of it (countercurrent, multi-stage extraction). Separation may be obtained by countercurrent extraction in a continuous column, either with or without reflux of the ex-

tracted product. The performance of countercurrent continuous columns is superior to the other methods if rapidity of settling and other characteristics permit their use and if the size of the operation justifies a continuous process.

Techniques Based on Solubility Changes Induced by Adding a Third Substance. A few liquid-liquid systems can be caused to separate into two phases by the addition of a third substance, which may be either solid or liquid, and may be completely or partially soluble in one or both components of the original solution. The process is not essentially different from the salting-out process described for the separation of solids from solutions. The major difficulty with this process is that when the original separation has been completed, the separating agent is still left in one or both phases of the separated material.

The equipment required for this process is similar to that used for solvent-extraction methods.

Techniques Based on Relative Freezing Points of the Constituents of a Solution. Many substances, liquids at ordinary temperatures, and in solution in a second liquid, can be crystallized out of the solution by cooling to temperatures below the melting point of one of the substances.

This technique is similar in operation to the ordinary crystallization of a solid from a liquid solution by cooling. It consists of cooling the liquid mass until solidification of the one substance occurs, followed by the separation of hardened solid from liquid by settling, filtration, or other means available for the separation of solid-liquid systems.

Obviously the separation must be completed at temperatures low enough to keep the solidified material from remelting. It is this requirement which sometimes makes the separation difficult, since the solvent may become very viscous and greatly impede the processes required for the separation of the solid from the liquid.

Techniques Based on Adsorptive Properties of Solids Toward Certain Liquids. *Use of Solid Adsorbents.* Traces of a liquid have long been removed from all kinds of liquids by treatment with fuller's earth, bauxite, clay, activated carbon, or a number of other solid materials possessing preferential adsorptive properties toward certain chemical substances. Generally, their use is

limited to the separation of two liquids when the adsorbable liquid is present in small quantity and not easily removable by other means; or when it occurs as colors, odors, or tastes in liquids, and is present only in minute quantities. The difficulty experienced in removing the adsorbed liquid and regenerating the adsorbent is often sufficient to discourage the use of the process. In some cases, the adsorbent is discarded when saturated with the adsorbed material. In other instances, however, regeneration is extremely simple. If so, the method may be suitable for removing a liquid in bulk from a solution.

Adsorbents may be either mixed with the liquid and then separated by settling or filtration, or packed in towers through which the liquid is passed by percolation. The fluidized bed treatment of adding solid adsorbents is an important technique for conducting this process.

Ion Exchange. Ion-exchange techniques can be applied to the separation of ionized liquids from a solution in a manner similar to the separation of soluble ionized solids.

Ion exchangers have become extremely useful and have capabilities for freeing solutions of traces of ionized materials not approached by any other method.

Chromatography. Chromatography is a technique for the separation of miscible liquids based on the fact that certain solid substances saturated with one adsorbed substance may still be able to adsorb a certain amount of another, usually with a release of some of the originally adsorbed material. Hence a second liquid may displace the first, there being a certain adsorption sequence according to the order in which substances are able to displace one another.

Although the principle is not new, having been discovered almost a half century ago, it has remained a laboratory technique for the separation and identification of complex organic compounds, and is only just now beginning to have commercial applications.

The chromatographic principle may be utilized by filling a long column with the adsorbent and slowly percolating the solution through the column. The various components are resolved from top to bottom into zones according to the adsorption sequence

with the more strongly adsorbed substances closest to the top. A solvent pumped through a charged column will force less highly adsorbed materials down and out of the column one by one.

Partition chromatography, another important technique introduced about ten years ago, has developed rapidly. In this technique the solid in the column adsorbs and holds stationary a liquid phase such as a water solution. Another solvent is then passed through the column to extract the first liquid phase. Enormous numbers of interchanges are obtained for very short lengths of column.

Techniques Based on Chemical Properties. When it is not possible to separate two liquids in solution by taking advantage of their physical properties, it is sometimes possible and practicable to make the separation, or to prepare the liquids for separation by physical means, by taking advantage of certain chemical properties. For the most part, chemical methods are a last resort, although there are many exceptions to this rule. Usually chemical treatment converts one substance to a gas which can be easily released, or to a solid which is precipitated from solution, or both simultaneously. The use of limestone beds or lime for neutralizing and removing traces of sulfuric and other acids which produce insoluble salts with the calcium ion is common practice.

19 : SEPARATION OF A GAS FROM A LIQUID

Techniques for Separating Gases from Liquids

For separating a gas in suspension in a viscous liquid

For separating a gas held in a liquid as a foam

For the separation of a gas dissolved in a liquid

Utilizing a reduction in partial pressure

Utilizing a change in solubility

It is not ordinarily difficult to separate a gas from a liquid; frequently the operation is as simple as allowing the liquid to stand for a short time. With the tremendous difference in the density of a gas and a liquid, a gas not actually dissolved in the liquid rises quickly to the surface of most liquids and is then discharged into the gaseous atmosphere above the mixture. There are, however, three situations relating to the separation of a gas from a liquid in which problems of considerable magnitude may have to be solved. These situations involve gases in suspension in a viscous liquid, in finely dispersed foams, and in solution in a liquid. The problems in each situation are entirely different.

The factors which must be considered in solving problems involving the separation of a gas and a liquid are less numerous than in other types of separation. The major problem is to get the gas into gaseous form in large enough bubbles and in a liquid of low enough viscosity so they will rise. The liquid should also have a surface tension which permits the bubbles to burst when they reach the surface. The factors which must be taken into consideration are as follows:

1. Condition of the gas in the liquid, whether free or in solution
2. Size of gas bubble

3. Viscosity of liquid
4. Temperature sensitivity of liquid
5. Solubility-temperature curves for gas in liquid
6. Surface tension of liquid
7. Corrosion properties of gas or liquid.

TECHNIQUES FOR SEPARATING GASES FROM LIQUIDS

Techniques for Separating a Gas in Suspension in a Viscous Liquid

The removal of small gas bubbles distributed throughout a mass of highly viscous liquid may present extremely perplexing problems, particularly if the liquid is corrosive or, like liquid glass, is at high temperatures. Gas bubbles may usually be separated from a liquid, even one of reasonably high viscosity, by simply allowing it to stand for a time. The bubbles will rise to the surface where they can be skimmed off or otherwise removed. Gentle stirring will sometimes gather and coagulate small bubbles, but this procedure must be conducted with extreme care so as not to reintroduce air mechanically into the mass.

When production requirements will not allow prolonged standing and when physical and chemical characteristics of the liquid mass will not allow other treatment for separating the gas, it may not be possible to remove it. This result may be observed in most silica ware, which is cloudy with small bubbles which were entrained in the mass while liquid.

Liquids which can be handled mechanically can usually be freed of suspended gas bubbles by kneading them in closed vessels which can be kept under vacuum during the operation. Werner and Pfeiderer and other mixers are made in styles which permit gas-tight enclosure of the charging openings so the mixer can be easily evacuated.

If the viscosity of the liquid mass can be reduced, the removal of suspended gas can be greatly accelerated. Therefore, in separating a suspended gas, lowering the viscosity by heating the liquid mass will nearly always expedite the separation. In some liquids a marked reduction of viscosity is obtained with small increase in temperature. Mixers can be obtained which are equipped

with a jacket for warming the contents, and if necessary, with both a jacket and a closure for the simultaneous application of heat and vacuum to the contents of the mixer.

Techniques for Separating a Gas Held in a Liquid as a Foam

Gases dispersed in finely divided bubbles in liquids whose surface tension prevents them from coalescing into large bubbles constitute a foam which may be nearly permanent in character. Even temporary foams of larger bubbles may be very troublesome to the operators of various types of equipment and processes. The breaking of such foams is often necessary and is sometimes a most perplexing problem.

The actual cause of foaming is somewhat obscure, but it frequently involves a mixture of a gas with a liquid containing a finely divided solid. The foam can sometimes be broken by removing this solid, but this approach is impractical in most cases.

Foam breaking can often be accomplished by the addition of various antifoaming agents, such as small amounts of kerosene, fatty oils, or acids. These, and any one of a number of proprietary agents which have been developed, will change the surface tension of the suspending liquid so that as the bubbles rise to the surface they will be released immediately, rather than collect in billowy masses of tiny bubbles.

Foams can sometimes be easily broken by a very slight change in pH. For example, many foams which form easily and copiously in very dilute alkaline solutions will be completely released in slightly acidic ones.

Surface foams can sometimes be broken by directing high-pressure steam or air against them. Breakage in the first of these two methods is effected by a combination of mechanical forces and by internal expansion of the bubble. In the second case, mechanical action alone is responsible for the breakage. Heat alone can sometimes be applied with success by suspending closed steam pipes in the space into which the foam may rise, or by locating radiant heat lamps to radiate against the foam.

A liquid containing a foam is sometimes pumped through jets and directed with high velocity against a baffle plate to break the gas bubbles. The mechanical action when the liquid

strikes the plate is often great enough to break and release bubbles of entrained gas.

For the most part, successful methods for foam abatement, especially when anti-foaming agents cannot be added, are developed by trial and error.

Techniques for Separating a Gas Dissolved in a Liquid

Gases dissolve in liquids in all ranges of solubility, depending on the properties of the gas and the liquid. Some gases are very soluble and are difficult to release from solution; others are relatively insoluble and reasonably easy to remove; still others are of intermediate solubility and present varying problems in connection with their release. The actual concentration of gas in a liquid is established by the concentration (partial pressure) of the gas in the surrounding atmosphere and the nature and temperature of the liquid.

Methods for effecting the release of gas in solution are, therefore, those which reduce the partial pressure of the particular gas in the gaseous phase, those which alter the solubility through changing the temperature, or those which change the nature of the liquid. Various combinations of these methods are also used.

Techniques for Removal of Gas by Reduction of the Partial Pressure. The partial pressure of a gas can be reduced by evacuating the gas space, or by diluting the gas above the solution with an inert gas. The vacuum method gives a much better opportunity for low-cost recovery of the gas, but may be ruled out because of the corrosive nature of the gas and the fact that, if recovery is necessary, only mechanical vacuum pumps can be used. The dilution method is often very effective and is normally quite cheap.

The vacuum technique can be conducted either batch-wise or continuously. Batch operation and the associated equipment is not at all complicated. A tank capable of withstanding the vacuum which must be applied and of sufficient size to hold the liquid, and equipment for producing and sustaining a vacuum are all that are required. Agitation of the liquid in the tank will usually facilitate the release of the gas and in general is to be recommended, especially if the liquid is at all viscous.

Continuous separation can be effected by spraying the liquid into an evacuated tank or tower, or by the use of several of the more open types of columns. The scrubbing action of the bubble plate or packed towers is not necessary in this operation, and the hydrostatic pressure developed in these towers should be avoided.

Dilution by an inert gas is also an operation which can be conducted as either a batch or continuous process. Batch techniques for this method are very simple and can be conducted in the simplest of equipment. A tank provided with a gas inlet in the bottom and fitted with sparger outlets, such as porous plates or drilled pipe, is required. The bubbling of the inert gas through the liquid will agitate as well as scrub the dissolved gases out of the liquid. Agitators such as the hollow-shaft turbine type which are used for mixing gases with liquids are quite adaptable to this type of operation. If the dissolved gas is not to be recovered, and if the scrubbing gas is air, the tank may be open.

Continuous gas-scrubbing techniques are also extremely simple to conduct. Bubble cap or packed towers are most suitable for this operation where excellent countercurrent contact of gas and liquid is desired and a pressure drop of a few inches of water through the tower is of no consequence. Columns can be vented to the atmosphere, but usually the gases leaving the tower are conducted to other equipment for further processing, purification, and recycling.

Techniques Utilizing Changes in Solubility. *Separation of Gas by Temperature Variation.* Gas solubilities may be profoundly influenced by temperature, most gases becoming appreciably less soluble as the temperature is increased. Consequently, it is often necessary only to raise the temperature of the liquid to cause the gas to be released. The operation is made continuous, either by injecting steam into a stream of the fluid or by heating the fluid in a tubular heater before it is introduced into an insulated spray tower or a cascade tower, or into a holding tank where a release of the gas is obtained.

In many cases, the nature of the heating requirements and the heat sensitivity of the liquid make other processes more desirable. It is easily possible to combine two or more methods for de-

gassing a liquid. For example, a liquid can be raised to the maximum allowable temperature and then blown with a gas or placed under a vacuum.

Separation of Gas by pH Variation. Some gases, quite soluble in neutral solution, become insoluble in solutions made strongly basic or acidic. Ammonia, which is very soluble in water, is rendered insoluble in solutions made alkaline with sodium hydroxide or hydrated lime. Carbon dioxide, on the other hand, can be driven out of solution by acidifying it with a dilute, nonvolatile acid. These techniques are usually combined with other methods, notably the addition of heat, in order to effect a better separation of the gas or a smaller usage of chemical or both.

Separation of Gas by Chemical Action. Gases may sometimes be changed by chemical action to become insoluble solid precipitates, or possibly even insoluble liquid or gaseous substances. Gases in solution may sometimes be converted to insoluble products by atmospheric oxidation, or may be reacted with solids or liquids to form salts which can be precipitated or crystallized out of solution.

20 : SEPARATION OF A SOLID FROM A GAS

Techniques for Separating Solids from Gases

Based on the weight of the particle

Gravity settling

Centrifugal settling

Based on the cross-section of the particle

Based on the inertia of the particle

Based on electrostatic phenomena

Techniques in which a liquid is used in separating a solid from a gas

Miscellaneous techniques

Ultrasonic precipitation

Thermal precipitation

The only types of solids whose removal from a gas presents a problem are those so small in diameter and so light in weight that they do not settle readily. All heavier particles will settle in all but the most rapidly moving gas streams and their removal is not difficult.

Although many of the methods for dust removal are of long standing, it was not until smoke abatement ordinances literally forced industry into the often profitable salvage of smoke that most of the development of methods for removing solids from gases was initiated. Waste gas must be cleaned before it can be discharged into the atmosphere of many localities; moreover, the gases evolved from chemical processing of materials are frequently laden with suspended solids which should be salvaged for economic reasons, or the gases must be freed of solids before they can be used in further processing.

Many techniques for separating a solid from a gas are available. Frequently the final decision regarding a technique to be employed will rest on economic considerations involving estimates of probable recoveries, cost of operation, and value of products

reclaimed. Separating must often be carried out even when the separated solids have no particular value, and the whole operation must be charged to loss. Management is likely to become very cost-conscious in such a situation, and the methods employed will often be only as effective as is necessary to meet the minimum requirements of municipal regulations.

Some of the more important physical and economic factors which relate to the selection of a technique for the separation of a solid from a gas are as follows:

1. Size of solid particles
2. Density of solid particles
3. Concentration of material in suspension
4. Volumes to be handled, total and amount per unit time
5. Minimum degree of separation required
6. Temperature of the gas and whether or not it is practicable to cool it
7. Whether or not the gas or the solid will be injured by liquid
8. Original cost of installation and cost of its maintenance and operation
9. Flammable or explosive properties of gas or solid
10. Corrosive action of gas on metal and cloth.

TECHNIQUES FOR SEPARATING SOLIDS FROM GASES

Techniques for separating a solid from a gas are based on five main principles relating to the properties of the solid substance, or modes of operation. These are as follows:

1. Weight of the particle
2. Cross section of the particle
3. Inertia of the particle
4. Electrostatic properties of the particle
5. The behavior of solids associated with liquids.

Techniques Based on the Weight of the Particle

Solid particles which are heavy enough to move unimpeded through a gas (and are not particularly affected by Brownian movement) can often be removed sufficiently well by either

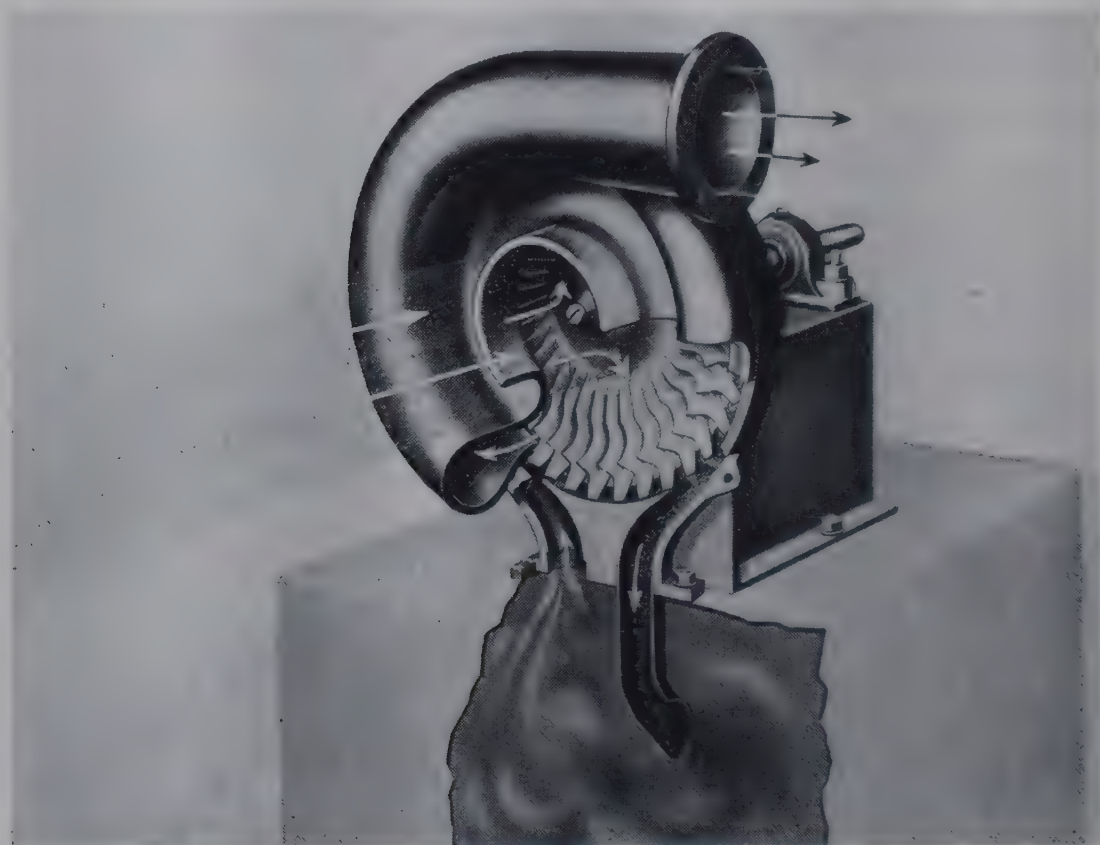
gravity or centrifugal separation to meet all requirements. Gravity and centrifugal separators are usually cheap to install and to operate. The pressure drop in these units is small; the precipitated dust can be removed easily, and is dry when removed; and gas at any temperature can be handled successfully. Their major disadvantage is that they are not successful when used alone for removing very fine solid particles from a gas stream.

Gravity Settling. In gravity separation, the gas stream carrying the solid is simply led to an expansion chamber of sufficiently large cross section that the gas velocity is much reduced. This technique is limited in effectiveness to solid particles above one millimeter (1,000 microns) in diameter, with a corresponding weight of one to two milligrams. Material particles of this size are classed as a medium dust or larger; unfortunately, however, the bulk of the material to be separated is usually much smaller than this. Because of their very low pressure drop, gravity separators are of importance in cleaning flue gases in natural draft systems.

The equipment for conducting this separation usually consists of long, horizontal, rectangular chambers, normally empty, but occasionally containing curtains, wires or screens to reduce eddy currents in the chambers. Horizontal plates will greatly assist settling for the same general reason that shallow settling basins for liquids will settle impurities more rapidly than deep ones. A commercial unit using plates has been built on this principle; it can be made much smaller than the empty chamber, but difficulties of discharging the solids and some problems in connection with the warping of a horizontal plate in a stream of hot gas discourage its wide use.

Centrifugal Settling. By increasing the velocity of the gas and leading or forcing it around a sharp corner or whirling it inside a cylindrical or conical shaped container, a force as great as 2,500 times that of gravity may be applied to the particles. Settling rates are thus greatly increased. The design must be such that the turbulence in the separator will not agitate the settled dust particles and reduce the effectiveness of the separation. The whirling action or change in direction may be imparted by the movement of the gas alone, or it may be promoted by mechanical

devices within the separator. Low-speed whirling motion can be obtained by introducing the gas tangentially into the top of the empty space enclosed by a pair of truncated cones set on top of one another to give a bulge at the waist. The cleaned gas leaves through the side near the center; the solids drop to the bottom of the lower cone.



(American Air Filter Corp.)

Figure 94. Centrifugal Dust Separator (Sectionalized view).

Cyclone separators, the most popular units of this classification, are made in a number of different patterns. The basic cyclone design consists of a short cylinder mounted above a cone so as to provide a conical bottom to the cylinder. A second concentric cylinder of smaller diameter projects downward into the unit. This is the exit pipe for the clean gas. A tangential inlet pipe near the top of the outside cylinder completes the separator.

Eddy currents, which tend to stir up the deposited dust, constitute the most serious defects of the ordinary cyclone. Several attempts to improve interior circulation of the gas and increase

the efficiency of separation have been successful and have led to many specialized designs of cyclone separators.

When the separation of fine particles of dust is desired, and when the inlet gas velocity in the nonmechanical separator is too low to impart sufficient velocity to the solids as they enter the cyclone, mechanical devices can be used to improve the operation. In these units the centrifugal force is supplied by a rotating element very similar in general appearance to the ordinary centrifugal fan. As a matter of fact, some separators are even designed to serve the dual purpose of dust separation and gas exhausting. Several styles of these separators are available. They are much more compact than the nonmechanical cyclones, and hence may be favored where space is at a premium. Difficulty may be experienced in their use, however, if the solid tends to adhere to the walls or rotating vanes.

Techniques Based on the Cross Section of the Particle

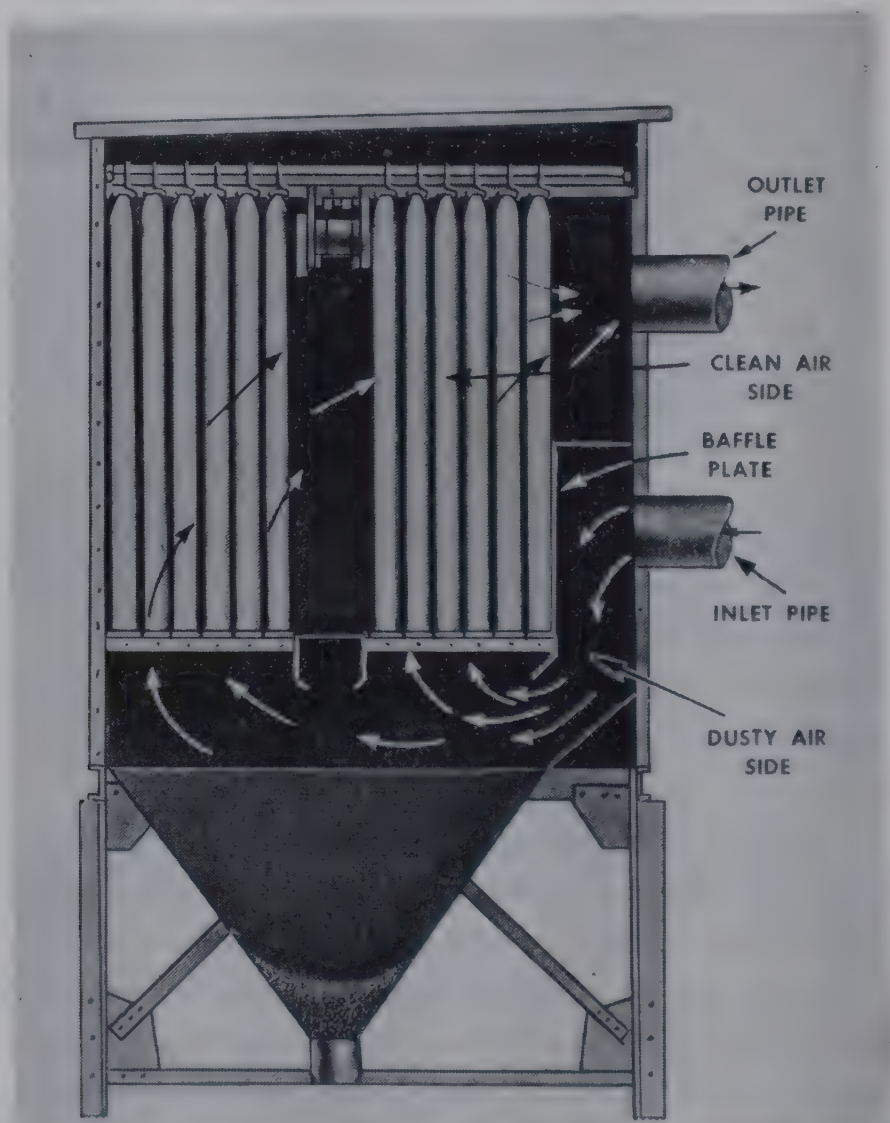
Almost complete separation of solids from a gas can be obtained by passing the gas through a filtering medium. Since extremely fine dusts can be handled with relative ease by this technique, filtration of solid-gas systems to remove the solid is widely practiced.

There are several difficulties, however, which limit its use. The major one is that few filtering media will withstand temperatures in the ranges of boiler plant flue gases or smelter gases. Another is that relatively large pressure drops are encountered. Further, filters are not adaptable to exceedingly large gas input, and are not useful for handling any solids which pack to form heavy deposits. They are not too effective for heavy dust loadings, but they may be made to give satisfactory service in this regard by placing a cyclone collector in the line ahead of them.

Filter fabrics are generally cotton sateens, but they may be woven also of wool, plastic, glass, asbestos, or metal. Cotton is cheapest and is satisfactory for general use. Wool will handle slightly acidic gases with much longer life than cotton. "Orlon," a new plastic fiber, will resist highly acidic gases and temperatures as high as 350°F. Glass, asbestos, and metal cloths have

been developed essentially for high-temperature work, gas at temperatures as high as 650°F. being handled successfully through filtering media made of these materials.

Since the pores in a filter surface are likely to be many times the size of the particle being removed, the actual filtering medium



(American Wheelabrator and Equipment Corp.)

Figure 95. Dust Separator. Stocking type.

is a built-up deposit of solid particles in and on the cloth surface, like it is in many of the solid-liquid filters. Consequently, the first service from a new filter surface is likely to be rather poor with respect to filtering efficiency.

Commercial filters are often built up of a number of stockings or bags which hang vertically in a housing. These are attached at the top to a metal frame which can be shaken by means of a

mechanical or electrical vibrator. The gas is brought into the unit from beneath the tubes, passes into the tubes through the open lower end and out the walls of the tube, leaving the dust behind on the inside of the filter fabric. The tubes are shaken at intervals to remove the collected dust. Many variations of this general design of air filter have been built.

Techniques Based on the Inertia of the Particle

Whenever a dust-laden gas impinges upon a solid body, the gas is deflected around the body, while the solid particle, having greater inertia, tends to strike the solid and stick to it. The wires and baffles sometimes hung in a settling chamber often become impingement separators, and a fairly large amount of dust will cling to their surfaces.

Several commercial separators are built in which this principle is employed. They are reasonably small, are not particularly affected by temperature of the gas, and are generally adaptable to insertion in existing flues or ducts. The pressure drop through the separator varies from one-half to one inch of water. The collection of dusts finer than 20 microns (0.02 mm.) in diameter is poor.

Fixed beds or packed columns provide this type of separation, but are usually not suitable for the separation of solids from gases because of the difficulty of plugging. Even when they are flushed with liquid, plugging may still be a serious problem. However, a movable bed has been developed. Gravel is continuously withdrawn from the bottom of this bed, cleaned by screening, and reintroduced at the top of the bed. The gravel beds are good impingement collectors; when placed in brick containers they have been used successfully up to temperatures of 2,000°F.

The commercial versions of the batt-type domestic air filter also fall into this class. These filters are filled with matted glass fibers, cotton, loose pulp, or metal packings. They are held in frames placed in the air stream, and if used dry are normally thrown away and replaced with new units when they become dust-laden. Their use is limited to air cleaning and other applications where the dust content of the gas, or the amount of gas to be cleaned is very small.

Techniques Based on Electrostatic Phenomena

When small particles which are suspended in a gas are brought into an electrostatic field, they become charged and will migrate to one or the other of the electrodes, depending on the charge they have assumed. Electrostatic precipitators based on this principle have been most successful and are very widely used. These precipitators, with ordinary performance, will separate 90 per cent or more of all the solids in suspension, regardless of quantity and size. The pressure drop as the gas passes through the unit is almost negligible. The initial cost of the installation is quite high, however, and power costs are considerable. Further, since there is always the danger of arcing within the unit, this type of precipitator cannot be used for the separation of solids such as flour, coal dusts, powdered magnesium or aluminum and others, which form flammable or explosive mixtures with air.

The precipitator is ordinarily built to operate in one of two possible ways. It may be either a single-stage unit in which ionization and collection are combined, or a two-stage type in which ionization is conducted in one section of the unit and collection becomes a subsequent operation. The types of precipitators vary somewhat in the manner in which these steps are conducted, and the method by which the collected solids are removed.

Techniques in which a Liquid is Used in Separating a Solid from a Gas

Water or other liquids may be used as a primary means of dust collection or as an adjunct to one of several other methods of solids-gas separation. The use of liquids greatly improves dust removal because reentrainment in the gas stream is eliminated. However, the gas must be cooled to the temperature of the liquid, which may be impractical. The gas is saturated with the vapor of the liquid, which may have some effect upon a process. Liquid losses may run to more than a gallon of liquid per 1,000 cubic feet of gas, and soluble gases are removed with the dust. The solid emerges in a liquid slurry, which must be further treated if the solid is to be recovered or the liquid reused. However, these disadvantages may not be serious, and techniques of dust removal

using water, oil, or other liquids continue to have many important applications.

Direct Use of a Liquid. Water and other liquids may be used in several types of equipment to literally scrub the solids out of a gas stream. There are several mechanisms by which a liquid may be used to remove a solid dispersed in a gas.

The first and most important is impingement. A water spray in a gas duct provides countless small droplets distributed over the region through which the dust-laden gas must flow. The dust particles collide with the water droplets and are trapped within the drop. A space filled with very small liquid droplets has infinitely more opportunity for absorbing solid particles by impingement than does the most intricate metal baffles.

A second mechanism is diffusion. Very fine dust particles may be moved into the surface of liquid droplets by Brownian movement. These particles are too small to be projected against the liquid surface with enough inertia to be entrained by impingement. Dust can be collected, therefore, by spraying water or other liquid into a quiescent gas body.

Humidification of a gas stream may cause flocculation of the dust particles and make them much easier to remove. If condensation takes place in a gas stream, the dust particles may act as nuclei for the formation of liquid droplets.

Any or all of these principles may be utilized in the design of gas scrubbers, a large number of which have been developed. Most of them are strictly impingement-type scrubbers, which employ various devices for distributing the droplets of liquid into the gas stream. They may be quite simple or fairly complicated. They may also have rather intricate means to remove the liquid spray from the gas stream. The general problem may be one of considerable complexity.

Adjunctive Use of Liquid in Solid-Gas Separation. The liquid in a dust-removal device may not be dispersed at all but may flow in a film over the collecting surfaces. In this case the liquid usually serves two important functions: it sweeps the collecting surface free of suspended solids and also effectively prevents re-entrainment of collected dust, hence making dust collectors much more efficient. Commercial equipment is available which

combines the use of liquid as an adjunct to dust removal with almost every primary method of solid-gas separation.

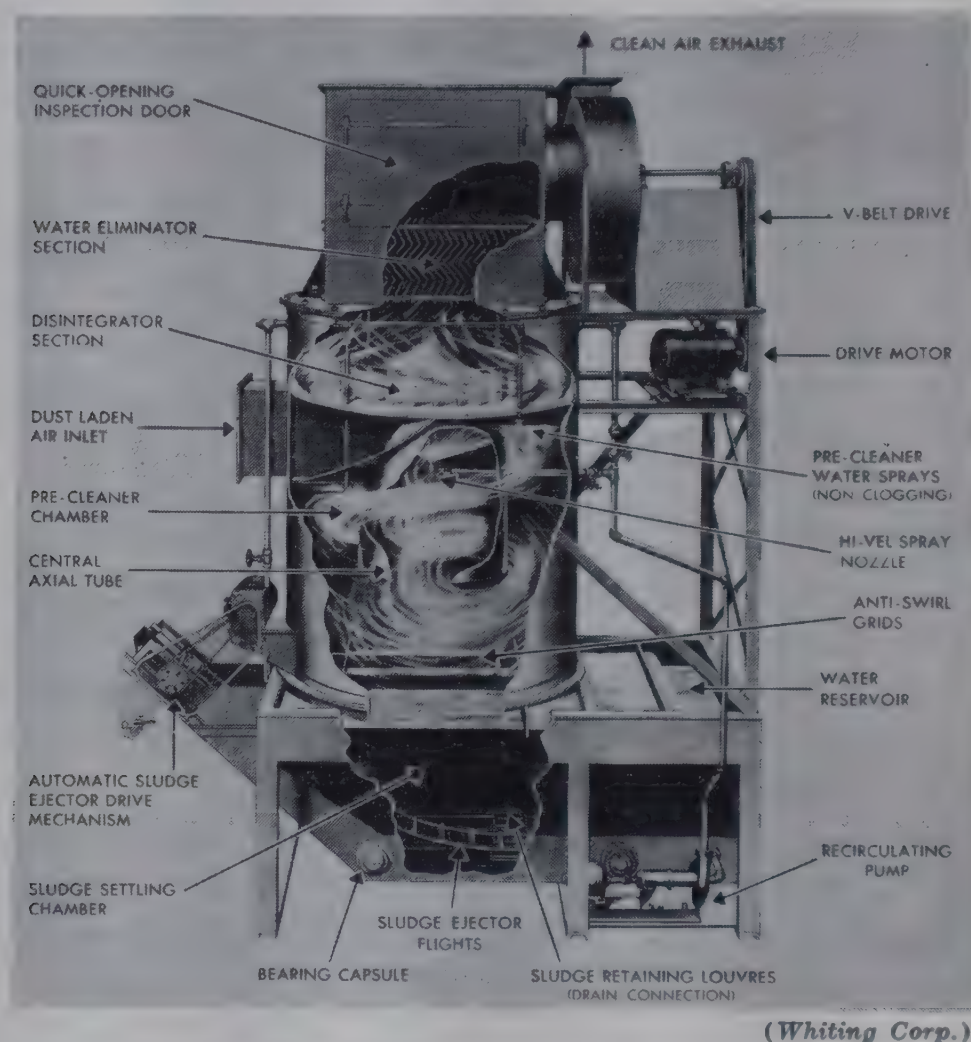


Figure 96. Dust Separator; Hydroclone (Vertical pattern).

Miscellaneous Techniques

Ultrasonic Precipitation. High-intensity ultrasonic vibration at frequencies of 1,000 to 10,000 cycles per second will cause collision of particles, which often results in their agglomeration to larger particles. This process is suitable for the separation of solids only when concentrations are greater than one grain per cubic foot. When the gas contains less than this amount, fine particles must be added to assist the agglomeration. Development of this technique had to wait for low-cost methods for the production of the ultrasonic energy. Now that these are available, pilot and full-scale plants have been built and operated for the separation of many substances from gas streams.

Thermal Precipitation. A method of dust removal is suggested by the fact that dusts will be repelled from heated surfaces by the increased molecular energy absorbed at these surfaces. No industrial application of this principle has yet been made.

21 : SEPARATION OF A LIQUID FROM A GAS

Techniques for Separating Liquid Droplets from Suspension in a Gas

Based on the weight of the liquid drop

Based on the diameter of the liquid drop

Based on the inertia of the liquid drop

Based on electrostatic phenomena

Employing a liquid as a removal medium

Miscellaneous techniques

As in the case of solids suspended in a gas, liquids can be held in almost permanent suspension in a gas in the form of tiny droplets. Although liquids tend to coalesce somewhat more readily than do solids, if the droplet is small enough, and the surface tension high enough, they can collide with one another repeatedly without any tendency whatsoever to coalesce into a larger drop.

The separation of a liquid from a gas presents problems similar to those involved in the separation of solid particles from gases but surprisingly enough, they are often much more perplexing. The tendency for a liquid to avoid coalescence can be related to its failure to adhere to solid surfaces, and in some cases, to adhere to or become caught in liquid surfaces. Mists and fogs of liquid substances are likely to be composed of much smaller particles than those of solid dusts. For these reasons some of the methods in use in solids-gas separations are impractical. Moreover, fogs often consist of highly corrosive substances, such as sulfuric acid, which cause corrosion of the walls of the separating apparatus. Also, liquids may cause shorting of electrical equipment.

The various properties of materials and the limitations of equipment must usually be examined very carefully in the case of liquid separations. The factors which must be considered in

selecting a technique for separating a liquid from a gas are:

1. Corrosive character of liquid in suspension
2. Surface tension of the liquid in suspension
3. Size of droplets
4. Concentration of droplets in the suspension
5. Quantity of material to be handled
6. Degree of separation required
7. Whether gas must emerge dry or whether water droplets or vapor replacing the other liquid is permissible
8. Whether the liquid in suspension must be kept free of water or other liquid
9. Possible difficulty of subsequent separations if liquid must be recovered
10. Toxicity of gas or liquid
11. Flammability of gas or liquid.

TECHNIQUES FOR SEPARATING LIQUID DROPLETS FROM SUSPENSION IN A GAS

The techniques for separating liquids from a suspension in a gas are similar to those suitable for dust removal. The principles upon which the techniques are based are identical, and much of the equipment which serves for solids separation can, with only slight modification, be made suitable for the removal of liquids from gases.

Handling liquids usually has one point of superiority over handling solids in that collection surfaces are likely to be self-cleaning, at least if they are vertical. Exceptions to this situation are encountered in the several tar separators in which the removal of the collected highly viscous materials may be much more difficult than the removal of deposited solids.

Continued reference will be made to the previous chapter in which techniques and equipment for dust removal have been described. In this section only the variations in techniques from those suitable for dust removal will be discussed.

Techniques Based on the Weight of the Liquid Drop

Because most liquid droplets are so very small that they are very much affected by molecular impact (Brownian movement),

gravity settling is ordinarily unsatisfactory, and even the conventional design of the cyclone is not very effective. Large droplets can be removed readily from a gas stream by mechanical entrapment, but a small-diameter cyclone or a mechanical centrifugal separator is required for removing very small drops. Cyclones used in series will also effect nearly complete removal of suspended liquid droplets.

The cyclone used in liquid separation should have a shield or skirt around the gas outlet duct. A portion of the liquid film which is deposited on the wall of the cyclone tends to creep up and across the roof, driven in that direction by the eddy currents within the cyclone. This film then runs down the outside of the outlet duct and is reentrained in the exit gas as it reaches the lip of the duct. A concentric shield around the duct or a conical skirt fastened to the duct will prevent the film from reaching the exit gas.

Techniques Based on the Diameter of the Liquid Drop

Filters, as a class, are not suitable for the separation of liquid droplets from a gas. However, filters of the batt type are used very effectively for liquid separation where they become, in effect, impingement separators. They can be made self-draining, can be washed, or can be cleaned automatically in the moving panel type of filter.

Techniques Based on the Inertia of the Liquid Drop

A number of applications of this principle are found in industrial equipment designed for removing mist from gas.

Zig-zag parallel plates are often used as impingement-type separators for removing medium-to-large size droplets. Most steam and compressed air entrainment separators are of this class.

Packed-bed separators are also very useful for removing liquid mists from a gas stream. These units can be constructed easily and, when packed with corrosion-resistant material, can be used successfully for removing acid sprays. The beds may be 2 to 6 feet in depth and as much as 30 feet in diameter for large gas throughput. Pressure drops are high (as much as 10 inches of water), and

unless the gas is free of dust, serious trouble from plugging is almost certain to develop.

Columns packed with wooden grids are often used for the removal of tar from coal gas. When the column becomes plugged with deposits of tar and solids, the grids are removed and cleaned, the tower being refilled meanwhile with freshly cleaned grids. The bulk of the tar in the form of a condensate is removed in tar traps (downcomer pipes dipping into hot water) before the gas reaches the tower.

Staggered plates, wires, cables, rods and other shapes inserted in gas ducts are used as impact separators; and while they are not extremely effective they do succeed in removing a considerable proportion of the larger mist particles. Batt-type filters should be mentioned again as another impingement type of mist separator.

Techniques Based on Electrostatic Phenomena

Liquid droplets, like solid particles, will become charged if placed in a strong electrical field, and will migrate to the pole of opposite charge. Hence, electrostatic separation of liquid mists from a gas can be performed as effectively as can the removal of dusts. The pipe precipitator, a nest of pipes through which the gas is passed, is the type most frequently used for the removal of mists. The discharge electrode, as in dust collectors, is a taut wire or rod suspended through the center of the tube. The metallic collecting electrodes (the pipes) can be replaced with carbon if the liquid which is being collected is corrosive. If the precipitated substance forms a conducting film, insulating materials such as glass, tile or wood can sometimes be used as the collecting electrodes.

Techniques Employing a Liquid as a Removal Medium

The removal of a fog or mist of liquid particles can often be accomplished by passing the mist-laden gas through a coarse liquid spray. The fact that this may, in turn, produce a mist of the scrubbing liquid may be either highly important and rule against its use, or it may be of no consequence whatever. The liquid mist which is removed is greatly diluted by the washing

liquid, and in most cases is probably not recoverable. Mist scrubbers can be built in any of the designs described under the section on scrubbing of dust-laden gases.

There is ordinarily little object in using a liquid as an adjunct to mist removal, since most liquid mists will wet the collecting surfaces and will, of their own accord, flow to sumps at the bottom of the collector. They can, however, serve to dilute and remove substances such as tar, waxes, and other highly viscous materials. Water, light oils, and other solvents are often used to slowly flush surfaces on which viscous liquids may be deposited. By completely covering such surfaces, the mist may not stick but may be drained with the flushing liquid to collection sumps.

Miscellaneous Techniques

Ultrasonic Precipitation. Liquid particles can be caused to flocculate by exposing them to ultrasonic vibration, in the same way as dust particles. The same requirement for minimum concentration holds here as for solids; therefore, liquid sprays must sometimes be added to improve coagulation. More conventional separation methods must usually be used to complete the mist removal.

Thermal Action. Converting mists into vapor is a possibility for their ultimate removal which should not be overlooked. While this is not a direct method of separation, it does convert all the material to one phase and prevent deposition of liquid on ducts or on other solids in the system. It is also sometimes easier to condense a vapor out of a gas stream than to separate a very finely-divided mist.

Chemical and Adsorption Techniques. Mists can sometimes be removed from a gas by chemical reaction with a solid or by adsorption on solid surfaces. These have the same general objection of high costs as chemical techniques for other separations.

22 : SEPARATION OF A GAS FROM A GAS

Techniques for Separating Gases from Gases

Based on the relative solubility in liquids

Based on the ability of solids to adsorb certain gases

Based on the relative boiling points of the gases

Based on chemical reactivity of the gases

Mixtures of gases are separated in order to prepare pure gaseous products, to concentrate gases for better chemical control and improved reaction conditions, and to remove diluents which lower combustion temperatures. Any or all gases in a mixture may be valuable, and it becomes essential at times to salvage one or all of the gases which are separated.

It has only been in recent years that industry has fully realized the profit which can be obtained by salvaging gases which formerly were wasted. In the recovery of solvents from painting operations and rayon spinning, and of volatile chemicals as waste from other processes, there have been repeated examples of complete amortization of the required equipment in the first thirty days of operation.

The property which is utilized most for the separation of liquid and solid particles from gases is the tremendous difference between the size and weight of these particles and the gas molecules. While gas molecules do vary considerably in size and weight, there are at present no commercial methods which can successfully use this principle to effect a separation of two gases. A technique for the separation of gases based on their different speeds of diffusion, which are related to molecular densities, has been used for isotope separation in the production of fissionable uranium, but the method is not yet commercially feasible.

Since all gases are completely soluble in one another, there is

no method by which any reduction of solubility can be used as a mode of separation.

The following factors should be considered in choosing a technique for separating a gas from a gas:

1. Solubility of the gas in liquid solvents
2. Response toward surface active agents
3. Condensation temperature and pressure
4. The chemical properties of the gases and their mixtures
5. The degree of separation required
6. The value of each constituent.

Usually there is little latitude in choosing methods of separating gases. Techniques founded upon the solution of gases in liquids or their adsorption on solids are so much more effective and cheaper than most techniques related to condensation properties and chemical reactivity that it is almost axiomatic that the former should be used, if at all possible.

TECHNIQUES FOR SEPARATING GASES FROM GASES

Operations involving gas mixtures are likely to be complicated by the necessity for handling large volumes for a relatively small weight of material. Virtually all techniques for gas separations involve the contact of a gas mixture with a solid or a liquid. Consequently, the problems encountered relate to the mixing of very low-density substances with the denser solids or liquids.

Techniques Based on the Relative Solubility in Liquids

Gases show marked differences in solubility in either pure liquids or liquid solutions. When gaseous mixtures are brought into contact with the proper solvents rapid separation usually takes place.

The solvent should be one in which the gas is highly soluble so that minimum quantities are required. Further, the solvent should not react with any of the gases in the mixture; or, if reaction occurs, it should be one which is easily reversed so that the gas can be readily removed from the solvent. The solvent should, if possible, be nontoxic, nonflammable, of low volatility.

and cheap. Inasmuch as one of the major gas separations is the removal of water vapor from a gas, it is of importance to note the types of liquid desiccants which are in use. These are calcium or lithium chloride solutions, diethylene or triethylene glycol, glycerol, phosphoric or sulfuric acid, and sodium or potassium hydroxide solutions.

The techniques employed for dissolving a gas in a liquid are the same as those used for countercurrent continuous mixing of gases and liquids. Batch operations are seldom used in gas separations on a commercial scale. The usual equipment for this operation is one of the several towers designed for gas-liquid systems. Packed towers, spray towers or chambers, perforated plate, bubble plate, and cascade columns are used. Towers such as the Feld scrubber in which the liquid is repeatedly sprayed into the gas stream, are also effective gas absorbers.

The complete operation for the separation of gases must usually provide for reclaiming the absorbed gas from the solvent and for the removal of solvent vapor from the undissolved gas. These operations may present problems of considerable magnitude.

Techniques Based on the Ability of Solids to Adsorb Certain Gases

There are a number of solids of porous structure which have a pronounced ability to adsorb certain gases. These include such substances as clays, chars, activated carbon, silica gel and other gels, alumina, and silicates. Some substances are highly specific in their adsorptive properties; others will adsorb quite broad classes of substances with about the same tenacity; still others have variable adsorptive powers. All these degrees of adsorption may be useful in various separations.

To be useful commercially the adsorbent must release the adsorbed gases with little difficulty, and be of such a nature as to permit easy and repeated reactivation. Further, the adsorbent should be coarsely granular so as to give free movement of the gas through beds. It should be hard, strong, permanent, and have high adsorptive capacity per unit of weight.

Adsorption units are usually closed tanks, in which the solid

adsorbent is held in a deep bed or on a series of shallow trays. Internal coils imbedded in the adsorbent mass, or made part of the trays, complete the unit. The depth of bed may vary from a few inches to several feet; the pressure drop through the bed and the power consumption are related to the depth. The coils provide cooling to take up heat released as vapors are condensed, and they may be used for heating when the adsorbent is reactivated.

The operation of a gas adsorption unit is normally intermittent. It can be made continuous by using two units, one of which is being reactivated while the other is in use. If some safety factor is desirable, or if two units in series make an appreciably better separation, three units operated in a cycle are more suitable.

The first cost of adsorption recovery systems is quite high due to the high price of adsorbents, but operating and maintenance costs are fairly low.

Techniques Based on the Relative Boiling Points of the Gases

In mixtures of gases having widely different boiling points, the gas of the higher boiling point can be converted to a liquid and drawn from the system. The process is the reverse of distillation for the separation of two liquids. While this method rarely provides complete separation of gases, it will separate vapors of fairly high boiling points at low cost. It is often used as a pretreating technique to reduce the load on adsorption units. It also provides a method of separating some gases which do not respond readily to other techniques.

Usually both compression and cooling are combined to remove easily condensable vapors, although either one alone will achieve partial results. The gas is first compressed and then sent to an after-cooler which is normally a water-cooled surface condenser. The gases leaving the after-cooler may contain a mist which should be removed if the gas is to be passed to an adsorption unit. Refrigeration may also be used for cooling and, if used, will cause an even greater proportion of the vapors to be condensed. The separation of oxygen from nitrogen by liquefying the higher-boiling oxygen is accomplished by the application of cooling and compression cycles.

Techniques Based on the Chemical Reactivity of the Gases

In many cases gases can be removed much more effectively by reacting them with some chemical substance than by any other method. If the reaction is easily reversible, the cost of such an operation may not be excessive, as it may be possible to recover the vapor removed easily and cheaply, and to regenerate the chemical for reuse. Even if this is not possible, other considerations may still make chemical reaction an interesting possibility for the separation of gases. Otherwise, chemical treatment is usually expensive, often difficult to control, and almost always means the loss of one or more of the original constituents. This technique should always be approached with caution and considered as a last resort. Rather than attempt to describe reactions in general terms, specific examples of the use of chemical reactions for gas separation will be cited.

Reactions with Solids. One of the best examples of a reaction between a gas and a solid for gas separation is the use of a solid desiccant for removing water vapor from air. Anhydrous calcium sulfate (Drierite) and magnesium perchlorate (Anhydron) are substances which remove water by forming hydrates. Both can be reactivated by heating, the perchlorate with considerable difficulty. When using barium or calcium oxides, a true chemical reaction takes place between these substances and the water they remove. Neither of these is easily reactivated. Drierite is the best desiccant, being capable of drying air to a dew point of -80°F . It is easily regenerated and can be so prepared as to indicate, by a color change, when it is exhausted.

The removal of carbon dioxide or of sulfur trioxide by passing them over beds of dry lime is sometimes practicable when they are present in a gas in low concentrations. The calcium carbonate formed by the action of CO_2 can be reclaimed.

Equipment for these reactions is very similar to that used for the adsorption of gases on a solid agent such as silica gel. The life of these reagents is somewhat limited, however, and in those cases where reactivation cannot be conducted in the absorber, simple and easy means for withdrawing the solid must be provided. Continuous units in which fresh material is added to the

top of a bed and the spent reagent continuously withdrawn from the bottom are possible.

Reactions with Liquids. Gases which are only mildly soluble in pure water may sometimes be made highly soluble in water solutions with which the gas readily reacts. One of the outstanding examples of the use of this principle is in the extraction of ammonia from coal gas. Here, sulfuric acid, a cheap chemical, is added to the water. Ammonia coming in contact with this acidic solution is instantly and completely dissolved, and can be recovered by neutralizing with lime. The cost of chemicals is not as great as the losses which would be incurred if the ammonia had been absorbed in water, plus the cost of recovery of the ammonia from a much greater volume of liquid.

An acid gas which occurs in large quantities in some natural gases is hydrogen sulfide. This gas must be removed because of its odor and corrosive properties, and because the sulfur dioxide formed in the combustion of the gas would be a nuisance to consumers. Further, the hydrogen sulfide and sulfur both have considerable commercial value. One of several very successful wet processes for removing hydrogen sulfide is to dissolve the sulfide in a dilute solution of arsenious oxide and soda ash. The solution is regenerated by blowing with air, whereupon the free sulfur eliminated rises to the top of the regeneration unit, where it can be skimmed off and recovered as elemental sulfur.

This is an excellent example of the separation of a gas by reaction in a liquid agent. Not only is the separation made much more complete than could be obtained by solution in water, but the chemical compound formed is easily and cheaply decomposed to regenerate the original solution and to simultaneously produce a valuable by-product.

Absorption equipment for these techniques is identical with that used for absorbing gases in water.

Reactions with Gases. The separation of gases by gaseous reaction ordinarily means conversion of one of the gases to a compound, such as water or carbon dioxide, which can be easily separated from the resultant mixture of gaseous products. Although it is hardly an economic process, nitrogen can be freed from oxygen by reacting it with hydrogen in stoichiometric pro-

portions. A heated grid will convert the oxygen to water almost instantly as the mixture of air and hydrogen is passed over it. When hydrogen is cheaply available—for example, as a by-product from an electrolytic chlorine plant—pure nitrogen can be prepared in this manner with a minimum plant investment.

Carbon monoxide can be converted to the easily removable carbon dioxide by catalytic reaction with steam. This is the principle of the process for converting carbon monoxide-hydrogen mixtures resulting from the partial oxidation of methane to a carbon dioxide-hydrogen mixture, as a preliminary to the production of hydrogen for ammonia synthesis. The carbon dioxide and excess steam are easily removed from the hydrogen, leaving behind a pure hydrogen residue.

SECTION VI

FURTHER TREATMENT OF
PRODUCTS FOR SALE, SHIP-
MENT, STORAGE, OR OTHER USE

23 : PREPARATION OF MATERIALS FOR MARKETING

Techniques for Processing of Solid Materials for Further Use

- Controlled crystallization**
- Combined crystallization and drying**
- Controlled precipitation**
- Molding techniques**
- Drawing techniques**
- Casting techniques**
- Compacting techniques**
- Fusion techniques**
- Sheeting techniques**
- Techniques for the prevention of caking**

Many products of the chemical industry, while they may be suitable for immediate reuse, are not in an acceptable condition for either extended storage, for shipment, or for sale to a consumer. Little can be done to change the physical properties of liquids or gases, but such is not the case with solids, which can be changed very appreciably in their physical condition and appearance.

There are a number of reasons for making such changes in a solid before it is placed on the market. Some of these are rather fundamental; others can be classed as custom demand. Some solid products are removed from the manufacturing process in a molten condition, and will solidify to form any size lump or cake, depending on the container in which they may be placed. If such materials have a high melting point, or if they cannot be handled safely, it would obviously be impossible to use them if they were cast in large blocks. Many solid materials are obtained as finely-divided powders. This condition often presents difficulties in further processing, adds many problems to those of storage and shipment and, if the material is combustible, may

greatly increase the fire and explosion hazard while in storage or shipment.

These are the fundamental reasons for after-treatment. There are others which may be as important from a business point of view. Customers' requirements must be met if the chemical manufacturer intends to stay in business. Requirements such as shape and size of material are sometimes so definite as to warrant complete description in the specifications of the product.

For the most part, the preparation of solid materials for trade, if they must be altered from their normal state, involves controlled crystallization or precipitation from solution, casting from the molten state, or molding into finished form starting with solids in a powdered or plastic condition.

Market requirements usually fix the condition of the end product made in any chemical process, and these, in turn, are the dominant factors in the selection of the technique to be used for its preparation. Other factors also contribute to the selection of an appropriate technique, namely:

1. Heat sensitivity of the material
2. Possibility of adding inert binders without injury to product
3. Quantity of material
4. Subsequent use or treatment to be given product.

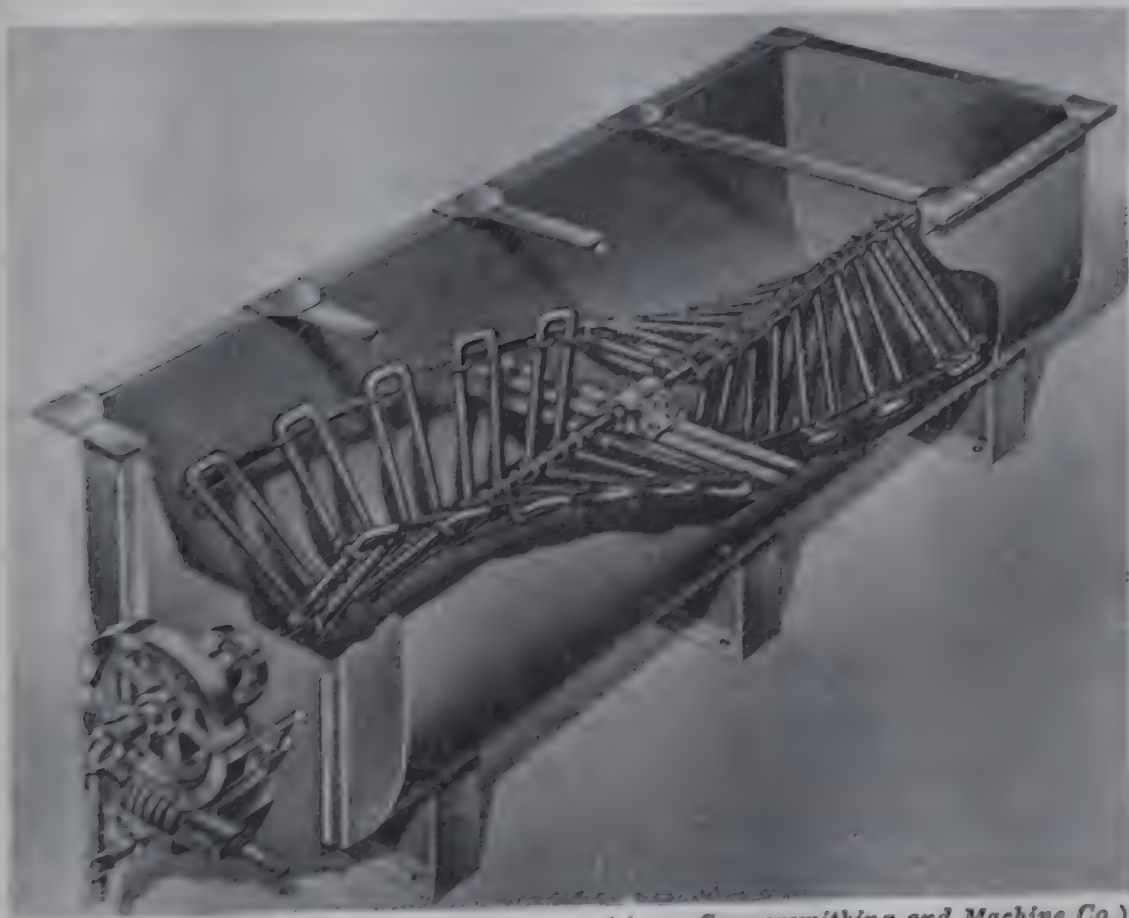
TECHNIQUES FOR PROCESSING SOLID MATERIALS FOR FURTHER USE

Techniques of Controlled Crystallization

The techniques of crystallization have been covered in the chapter on the separation of solids from solution, and the precipitation of a solid as a method for its separation from solution has also been described. This discussion is an extension of these descriptions to include a review of some of the techniques whereby crystallization and precipitation can be controlled to give specific properties to the solid products.

When crystal size is an important item in fixing the value of a solid material, temperature and concentration during the crystallization must be controlled very closely; seeding during

evaporation or cooling must be done cautiously to get exact amounts of material having the correct size of seed crystals; and the progress of the crystallization must be observed continuously. Vacuum crystallization often provides a much more satisfactory means for crystal size control than jacketed intermittent or



(Acme Coppersmithing and Machine Co.)

Figure 97. Batch Crystallizer.

continuous crystallizers. In general, the more slowly a crystallizing mass is cooled, the more uniform the crystals will be, and the more accurately final crystal sizes can be regulated.

Combined Crystallization and Drying

Combination spray drying and crystallization techniques have been developed whereby a regulation of the size, concentration and temperature of the droplets of liquid which are fed to the dryer will give crystalline agglomerates or granules of the size required for the market.

One of the principal advantages of this technique is the pro-

duction of a hollow spherical particle which is in considerable demand. This particle shape is caused by a tendency to form a skin of precipitated material over the droplet as it dries, and as the drop shrinks away from the skin it forms the hollow spherical globule. Many soaps, made into beads in this way, give good bulking properties, go into solution rapidly, and yet are free from fine, dusty material.

Controlled Precipitation

A few chemical substances, notably the gels, are precipitated from solution to nodules which have, when dried, the proper density, size, and surface characteristics. The preparation of silica gel is one operation of this kind. The hard, glassy, sand-like particles are formed by the reaction of liquid sodium silicates and sulfuric acid under very carefully controlled conditions of concentration, temperature, rate of addition, and mixing. The coagulated mixture is washed carefully and is dried under rigid control to give the proper size of dried granules.

Molding Techniques

If solid granular or powdered material can be softened by heat or by a solvent which is easily removed, or if it is in a molten condition, it can usually be hardened into whatever shape or size that may be desired. This is of tremendous interest to any user where shape as well as size may be an important physical property of the solid used in a process.

The techniques in this category are largely those of plastics handling, although they can apply equally well to other materials of similar character. The different mechanical molding techniques are extrusion molding, injection molding, compression molding, transfer molding and air pressure molding. Hand molding is also used to a limited extent, mostly in forming ceramic ware.

Extrusion Molding. Extrusion molding is the technique whereby softened material such as plastic, rubber, or soft metal is forced from a chamber or barrel through an orifice (die) of proper shape to give a product of desired and uniform cross-section as it emerges from the opening. Actually the process is

an art. The cross-section of the extruded section often differs considerably from that of the opening, being influenced by a number of more or less independent factors. The problem of selecting an orifice to produce a specified section is usually one involving lengthy experimentation.

The equipment for extrusion techniques has several features in common: a method for pressing the softened material through the orifice, a means for keeping the material soft as it is forced into the cylinder ahead of the orifice, and a means for forming the extruded material into the proper size or shape (the orifice or die).

The major differences are in the method of feeding. Actually two types of operation are possible: an intermittent method in which the material is fed to the machine in chunks and forced through the die by hydraulic ram, and a continuous method in which the material is fed to and pressed through the die by means of a screw. The latter method is more suitable for materials requiring relatively low pressures and temperatures below 300°C. These conditions more or less limit its use to rubber, plastic, food, and other soft materials. The ram is better adapted to handling metals, and is best for extruding smokeless powder and nitrate plastics.

Extrusion molding is used almost exclusively for forming the transparent plastic sheeting for safety glass laminates, transparent wraps, and plastic pipes and tubing. It is also the technique used to produce the millions of pounds of synthetic filaments used each year. In the latter case the plastic is soft enough to be pumped, and both extrusion and drawing operations combine to complete the technique. Extrusion techniques are often used to produce noodles, which are then broken to form short cylinders as a finished product. Extrusion techniques are the only ones of this group which are used to produce material other than finished plastic or glass items.

Compression Molding

The technique of compression molding consists of placing an accurately measured charge of the material to be molded in the bottom half of a heated metal die, and then lowering the upper

or companion die into place and forcing it, by means of a mechanical or hydraulic press, to close against the plastic. Both upper and lower dies are heated until the mass has softened and filled the space between them. When this has been done, the steam is cut off and cold water run through the dies until the molded piece has set rigidly enough to be removed. This is the oldest type of molding and is still widely used.

Transfer Molding

In transfer molding the material to be molded is heated in a chamber located directly above the heated mold and connected to it by a conical-bore channel. When the mass in the upper chamber is soft it is forced into the mold by means of a plunger which is driven into the heating chamber by a hydraulic press. Transfer molding is especially valuable in the manufacture of plastic pieces containing delicate metal inserts. The soft plastic is less liable to disturb or damage inserts than the powders used in conventional compression molding.

Injection Molding

In the injection molding process, a plastic of a thermo-plastic nature is fed in granular form to a hopper above one end of a horizontal cylinder. The opposite end of the cylinder is heated by electric resistance heaters or by circulating hot oil. A plunger forced into the cylinder moves a charge of the granules into the hot zone of the cylinder, and at the same time a charge of hot softened plastic is forced out of the hot zone directly into a cold mold which was positioned to receive the plastic before the start of the stroke. As the plunger returns, the mold opens, dropping out the molded piece, then closes; a new charge of cold granules drops from the hopper into the cylinder, and the cycle is completed.

Air Pressure Molding

Most hollow glass items are made in a molding process in which the semi-molten glass is forced against the sides of a retaining mold by means of compressed air directed into a globule of molten glass which is suspended inside the mold. The glass

bottle making machine is quite complex in actual operation but it uses this simple principle of operation.

This molding technique is adaptable to any operation in which the material is fairly soft, is quite tacky so that it does not easily pull apart, and will harden quickly upon coming in contact with the walls of the mold.

Drawing Techniques

Materials like molten glass which are at too high a temperature to be handled in intricate metal molds and, though tacky in the molten condition, will harden rapidly on cooling by air, can be pulled into long continuous strands of uniform cross-section by drawing the material through an orifice of the correct size and shape. Ordinary window glass and most glass tubing is made by techniques based on this mode of operation. This may also be applicable to the production of broken cylinders as the shape of a chemical product.

Casting Techniques

The casting of materials usually involves a fluid mass which flows into a mold and assumes its shape and solidifies, either by freezing (if molten) or chemical action (polymerization). Casting normally involves handling molten material, although it can be applied to certain materials which require some period of time to harden.

Mold Casting. Many different molten materials are cast into solid shapes for further use, for storage, or for sale. Virtually all metals, for example, are cast into "pigs" of various shapes and sizes for further use. These pigs may vary in size from a few ounces to a ton or more, depending on the volume of production and the value of the material. They are cast in a generally similar fashion, however. The molten metal is poured into open refractory molds, inside of which the metal hardens in the shape of the mold. All molds are larger at the top (or at the bottom) than at the opposite end. In this way the solidified metal is easily removed. In steel manufacture, open hearth or Bessemer steel is poured into molds larger at the bottom than at the top and the metal is removed by "stripping" the bottomless molds from the

ingots. The molds are placed, bottomless end down, on a flat surface to receive the molten charge. Forming metals into intricate shapes in foundry practice is another form of solid mold casting.

Sodium hydroxide is an example of a chemical substance cast into a mold. Here the molten caustic is poured into light-weight steel drums. The hardened mass is not removed from the drum, which forms an air-tight "skin" over the caustic block. Cast shapes of caustic such as sticks and pellets are familiar forms found in many laboratories.

Sheet Casting. Trade demands sometimes require that material be delivered in sheets or flakes. Both these forms can be developed through casting procedures.

One of the best examples of flat sheet casting is found in the glass industry, where all plate glass is made by pouring glass into a level mold. The usual technique employs a movable flat mold which receives the glass and immediately passes under a leveling roll which flattens the glass on the supporting flat plate. This method of sheet casting is rarely applied to chemical production.

Sheet material can also be formed by chilled polished metal drums dipping into a molten mass of the material, or more uniformly by having two rolls with small clearance receiving the molten mass in the pocket formed between them. The double drum arrangement is also better for materials which do not stick well to the drums.

Plastic materials can be drawn from the rolls in continuous sheets. Brittle material is flaked by stripping the rolls with sharply curved doctor blades. The drum flakers are simple in operation and can be successfully applied to a wide variety of chemical products that have a fairly sharp and reasonably high melting point.

Revolving tables or traveling metal belts have also been designed for flaking service. The melt is fed to these devices from the top; very thin to very thick flakes can be produced at will.

Material cast in sheets may often be shredded or granulated, as well as flaked, to meet consumer demands.

Compacting Techniques

Since dry powders are often difficult to handle, a number of methods have been developed to produce granular or lump materials from these powders by pressing them into dies or molds.

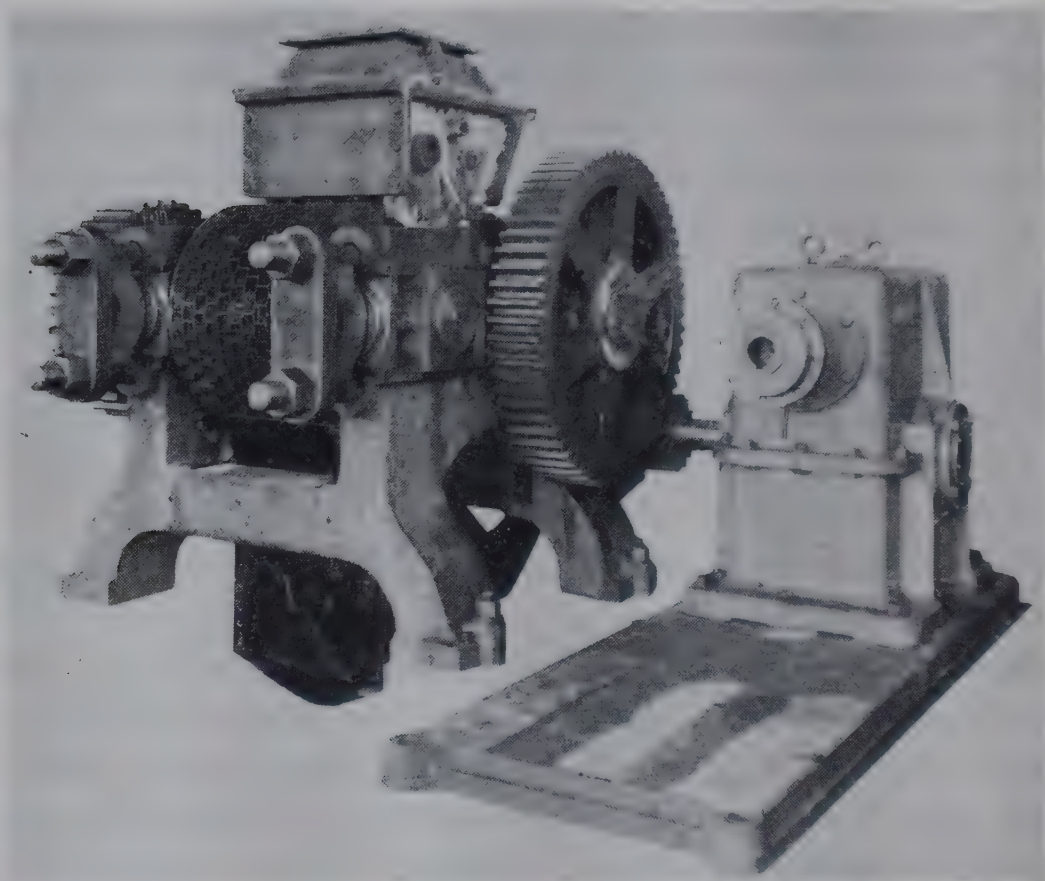
Tableting. Machines were devised years ago for compressing dry chemicals into tablets for use in the pharmaceutical trade. They have also come into general use for compressing candy mints, laundry starches, and many other domestic items where the added convenience of the tablet form more than compensates for the extra cost. More recently they have become of industrial interest in the preparation of chemical catalysts, explosives, plastic preforms, dyes, abrasives, and many other items. In many instances, as in the pharmaceutical industry, the size of the tablet may be important as representing a basic unit of material; in industrial applications the number of tablets rather than weights or volumes can be taken as a basis for formula computation.

The tableting machine is essentially a cavity large enough to hold the requisite amount of powder, and a hydraulic or mechanical pressure plunger which forms the opposite face of the tablet and closes the cavity. Powder is fed to the cavity, the plunger compresses it and an ejector lifts the pressed pellet out of the depression. Special rotary presses are designed to make up to 4,000 tablets per minute. The material to be pressed should be free of air and must be granular in form. A binder of inert material, such as starch or sugar, is sometimes needed to make a firm and strong tablet. Cavity and punch faces usually have to be lubricated with oil, waxes, stearic acid, talc, graphite, or similar lubricating materials.

Pelleting. Free-flowing materials can sometimes be compressed into small hard lumps by an operation known as pelleting. The die in this case is ring-shaped and the material is squeezed through it by a roll moving over the inside surface of the ring. A knife on the outside of the ring cuts the extruded material into pellets. The original machine of this type was used for pelletizing animal feeds. Pelleting machines are now used for many chemicals

whose characteristics will permit compression to compact shapes.

Another type of pelleting process makes roughly spherical lumps of powdery material by mixing with it a small amount of liquid at ordinary temperatures, and then rolling this material on the inside of a unit similar to a rotary kiln until it has formed into small lumps. These are then removed and dried.



(Vulcan Iron Works)

Figure 98. Briquetting Machine.

Briquetting. Briquetting is an operation very similar to tableting except that the pieces produced are larger, and in many cases quite carefully designed to give certain characteristics to the resulting product. Materials such as fuel and ore are often briquetted so they can be handled easily in furnace or reduction operations. The briquetting machine is a large-scale tableting machine, and is operated very similarly. Binding materials are usually materials such as tars or waxes. Binders which are water-soluble will require the briquette to be water-proofed if it is to be stored out-of-doors.

Powder Metallurgy. In the last decade a completely new metallurgical science has been created based upon the fact that finely-divided metals can be incorporated with a small quantity of lubricant, pressed into shape, and then heated in a nonoxidizing atmosphere to develop a porous metal piece. These materials are extensively used in self-lubricating bearings, in the manufacture of small machine parts, and many other applications. The ordinary briquetting presses can be adapted to powder metallurgy without appreciable change except in the dies used.

Roll-pressing. Some loose materials can be compacted in long sheets by passing them between a pair of rolls where they are pressed in the same manner as in a briquetting machine. The pressure at the nip of two heavily loaded rolls is very high and compacting approaches a maximum. Bulky materials may be pushed backward and pile up in front of the rolls rather than become caught between them. To eliminate this difficulty, rolls operating in tandem with each pair set with decreasing clearances, or a positive conveyor feed, or both, may be used very effectively. The compressed sheet may be cut into sections and be sold as such, or may be broken down to coarse granules.

Spheronizing. A patented process, originally developed to pelletize carbon black, has been found to be applicable to other materials as well. In this technique the material is subjected to turbulent mechanical action in a mixer with specially designed agitators. The material gradually gathers into small lumps with a considerable reduction in bulk density. The process has to be watched with care in order to stop it at exactly the right time; otherwise the lumps will be reground.

Fusion Techniques

Ground ores and other finely-divided solids must usually be enlarged to prevent them from being carried out of the apparatus when they are subjected to the high velocity of the gases in the reaction. Some materials, such as cement, are stored as lumps to minimize deterioration. Lumps of these materials can sometimes be formed by fusion. The several methods used for agglomerating lumps of material through high-temperature fusion are known as nodulizing, agglomerating, or sintering.

Nodulizing. Nodulizing is a process wherein fine particles are heated to incipient fusion, and rolled around the interior of the heating kiln where they form into nodules, or ball-shaped semi-plastic lumps. These, on cooling, form hard pebbles. The equipment required for this operation is an ordinary high-temperature rotary kiln.

Agglomerating. Dry materials are agglomerated by the addition of a second substance, often in very small quantity, which will fuse, causing the powdery material to be caught in it and roll up into balls in the same manner as described for nodulizing. The equipment is the same as that used for nodulizing, except that somewhat closer control must be exercised. An excess of the gathering agent will cause the material to pile up on the walls of the kiln, while too little will fail to form the lumps.

Sintering. In the sintering technique, the finely-divided solid is mixed with fuel and placed in a moving apron-type grate. It is ignited on the top surface and burned by air being drawn downward through the bed. The heat produced as the fuel burns fuses some of the solid, which is then cemented together as the fused material is cooled. The product may break as it falls off the end of the belt, or may be led to crushers where it is reduced to a granular mass.

Sheeting Techniques

A method sometimes used for preparing solids for storage or shipment is that of sheeting, in which the solids are gathered from liquid suspension on the surface of a filter cylinder or on a traveling screen belt. If the solids cohere into a sheet having sufficient strength, they can be either reeled on large rolls, or cut, or folded into packages. Sheets, thus formed, are usually pressed and dried before packaging as rolls or as folded or cut sheets.

Techniques for the Prevention of Caking

While it is highly important that certain powdered materials be converted to granules or larger particles for shipment, storage, or further processing, it is equally important to prevent, if possible, granular materials from hardening into solid lumps in the

bags or boxes in which they may be packed, or even more important to prevent them from caking in the storage piles or bins in which they may be placed.

Caking is usually caused by exposing crystalline materials alternately to damp and dry atmospheres. The moisture penetrating a pile of such crystals will be taken up on the crystal surfaces, producing tiny spots of saturated solution on the faces of the crystals in the mass. If the exposure is long enough, all the voids may become filled with this solution. When this moisture is re-evaporated the mass solidifies into a single solid lump.

For relatively complete protection against caking, the crystals must be kept out of contact with air in tightly closed drums, bottles, or vapor-tight packages; if this is not possible, storage in dry, well ventilated areas may help. The crystals themselves, if uniform in size, will have the greatest amount of voids, and will therefore be better ventilated in the pile, and will tend to resist caking. Coarse crystals will show less tendency to cake than fine ones. Very pure crystals are less affected by this difficulty than those containing traces of certain impurities.

Another remedy, somewhat effective in those cases in which it can be used, is to dust the crystals with a powdery inert material which can absorb some moisture without changing its properties. Table salt, for example, is commonly dusted with magnesia or with calcium phosphate. Other materials, such as hydrated salts, may sometimes be self-dusted by drying under such conditions that a thin layer of anhydrous salt is produced on the outside of the crystal; or they may be dusted with the anhydrous powder.

24 : MEASUREMENT OF PHYSICAL AND CHEMICAL QUALITIES

Quality Control of Materials

- Control of raw materials

- Control of intermediates

- Finished products

Methods of Sampling

Methods of Measurement of Physical and Chemical Qualities

- Conventional laboratory bench methods of chemical analysis

- Electrometric methods

- Optical methods

- Other physical methods

The chemical engineer is usually required to produce materials which are subject to rigid specifications governing compositions and properties. The end uses to which the same material may be placed may require that it be made to quite different specifications. The presence of small quantities of impurities may be quite deleterious in some cases. The chemical engineer is required to know how such impurities affect given processes, how to detect their existence and to determine quantitatively the amounts present. The control of process variables such as temperature and pressure is of no greater importance than is the chemical control of materials. Knowledge of the concentrations, purities and other factors relating to the materials is also of paramount importance to the material accountant, who must have reliable information upon which to base inventories and cost analyses.

Chemical and quality control may be secured by the use of many chemical and physical methods.

QUALITY CONTROL OF MATERIALS

Control of Raw Materials

The control of any chemical process requires an accurate knowledge of the purity of all raw materials used in the plant,

all intermediates, and all treating agents. All raw materials used in a chemical plant, regardless of their source, must be subjected to strict control, both chemical and physical. The chemical engineer should examine the raw materials available and prepare rigid but reasonable specifications governing their quality and properties. The effects of impurities must be known, and allowance made for their presence and effects.

After specifications have been prepared, it is the duty of the laboratory technician, often under the direct supervision of the engineering staff, to examine and analyze all raw materials entering a plant to make certain that the specifications are met. If the situation is such that impurities in raw materials may vary in kind or amount from lot to lot, it becomes the task of the chemical engineer working with the chemist to prepare operating directives for proper plant treatment of the various lots.

Control of Intermediates

Intermediate materials introduced into a chemical process may be manufactured in the same plant or purchased from outside sources. In either case, the technical staff concerned with the consuming operation should subject the intermediates to careful examination to make certain that they meet specifications. Many operational difficulties can be traced to carelessness in making unjustifiable assumptions concerning purities of materials made internally or purchased under specifications.

Finished Products

In considering the purities of raw materials and intermediates, the chemical engineer is concerned principally with the impact of the quality of these materials upon plant operation. The requirements of purity of the final products are usually established upon the basis of consumer demands balanced against plant capability; it should be the considered effort of every chemical engineer to obtain a product of the highest possible purity, with minimum deviations from prescribed specifications. It is the responsibility of the chemical engineer to bring quality and effective production schedules into as good balance as possible.

METHODS OF SAMPLING

Technical personnel do not always realize the critical importance of proper sampling. Sampling is one of the most critical of analytical operations, and yet its importance is so frequently overlooked that much analytical work is virtually worthless. A proper sample must be representative of the entire lot from which it is taken.

Well-standardized procedures for hand-sampling have been devised and are in common use; but because of labor costs, the trend is toward automatic machine sampling. Samplers are not standardized. Most are ingenious devices tailored to the material being sampled and the conditions obtaining at the sampling point. This subject has been discussed in somewhat greater detail in Chapter 10. Complete descriptions of standard procedures for the preparation of samples are given in publications of the American Society for Testing Materials.

METHODS OF MEASUREMENT OF PHYSICAL AND CHEMICAL QUALITIES

Conventional Laboratory Bench Methods of Chemical Analysis

Gravimetric Methods. Gravimetric methods of analysis normally depend upon the formation of an insoluble compound by treatment with suitable reagents, the absorption of the products of a reaction in the proper absorbent, and other operations susceptible to the determination of weights. Knowledge of the relationships of reactants and products permits calculation of the composition of the initial sample of material. These methods require a minimum investment in apparatus and laboratory. Gravimetric methods are usually long and tedious. In many instances, the length of time required to obtain results by the application of these methods precludes their use in plant control where analytical data may be of little value in a very short time after the sample is taken. These methods are, however, usually quite accurate and are often used to check the accuracy of other more rapid methods.

Virtually no sample is too small to be analyzed. Modern tech-

niques of microchemical analysis permit quantitative analysis of solids, liquids and gases in milli- and microgram quantities.

Volumetric Methods. In conventional volumetric analysis, the volume of a reagent, measured in a burette, required to complete a reaction (reach an "end point") may be made to indicate the concentration of a constituent in a sample. The end point may be found by observing a color change of an indicator (internal or external) or the formation of a precipitate. These methods are much faster than gravimetric methods, though frequently of a lower order of accuracy.

Electrolytic Methods. Electrolytic methods, in a sense, may be classified as gravimetric, since they depend upon a determination of the weight of an element or compound which is deposited upon an electrode of an electrolytic cell by action of a direct current. In brief, the electrode, usually platinum, is weighed before and after the deposition. The increase in weight can be used to calculate the analysis of the original sample.

Gasometric Methods. Gasometric methods depend upon the ability of certain reagent solutions to absorb selectively the various constituents of a gaseous mixture. The apparatus consists essentially of a group of absorption tubes, each containing a reagent solution selected for its ability to absorb some single known constituent of the gas mixture. A measuring tube and a leveling bulb permit a measured volume of the gas to be introduced into the absorption tubes and can be used to measure the reduction in the volume of the gas resulting from absorption.

Electrometric Methods

The traditional methods of analysis, while still widely used, are being supplanted by improved methods employing electrical devices designed to make the determination of the end points of reactions both faster and more precise.

Conductometric Methods. Conductometric methods of analysis depend upon a determination of the conductivity of the system in which the reaction is taking place. The conductivity is a function of the mobility of the ions present in the solution. When the ions of the reactants are replaced by those of the products, a sharp change in conductivity may occur. In the case

where one of the products is precipitated, a point of minimum conductivity may be observed.

Successful application of these methods requires a carefully constructed conductivity cell employing platinized platinum electrodes, a source of alternating current of high audiofrequency (1,000 cycles per second) which is free from harmonics, and a suitable resistance-measuring bridge. Modern units are completely self-contained, having a built-in current source, bridge, and balance-indicating devices.

Potentiometric Methods. The end point of a reaction may be determined by potentiometric methods, which depend upon the change of the electromotive force of a galvanic cell containing the reacting system. One of the half-cells is a reference half-cell of known composition; the other half-cell consists of an electrode immersed in the solution to be investigated. As the solution is titrated, the concentration is altered, and if the voltage, measured by a potentiometer, is plotted against the quantity of reagent added, a break in the curve indicates the end point of the reaction.

The normal hydrogen electrode is, by definition, the standard reference electrode, but it is wholly unsuited for industrial use. In practice, the reference electrode is usually a calomel (mercurous chloride) electrode saturated with potassium chloride. This electrode does not have zero potential, but it may be calibrated with respect to the ideal hydrogen electrode.

By substituting a millivoltmeter for the potentiometer and proper calibration of the instruments against concentrations of known ions, such as, for example, hydrogen ions, the instrument can be made to read concentrations directly.

Polarographic Methods. Polarography is an electrochemical method of analysis which contains certain features of both potentiometric and electrolytic methods. In this technique, potentials are measured while a current of known value is caused to flow through a cell in which one electrode is a so-called dropping mercury electrode. The current employed is of low value, and since the time of examination is short, the solution being analyzed is virtually unchanged. The current is plotted against the observed voltages, giving a curve which indicates the element present and its concentration. The name "polarography"

is derived from the current-voltage curve, which is a graphical representation of the polarization of an electrode. It should not be confused with the term "polarimetry," which refers to measurements with polarized light.

Optical Methods

Optical methods for determining chemical and physical properties of substances are in wide use. In general, these methods are noted for ease of application and manipulation and the high accuracy of the results obtained by them.

Polarimetric Methods. Polarimetric methods are based upon the property of many substances, both in the solid crystalline state and in solution, of rotating a beam of polarized light. With a prescribed weight of sample in the solution, the degree of rotation will be a measure of the amount of optically active substance present.

A polarimeter consists essentially of a light source, a condensing lens, some type of light-polarizing prism, a tube with optical glass ends containing the solution to be examined, an analyzing prism which can be rotated, a scale for measuring the degree of rotation of the beam of polarized light, and an eyepiece.

Refractometric Methods. Refractometric methods are based upon the fact that a ray of light, when passing from a medium of lesser density into one of greater density, is refracted or bent toward a line normal to the plane boundary between the two substances. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is defined as the index of refraction. The value of this index is a constant for any homogeneous material for any one wave length of light. Since the index of refraction is a characteristic property of transparent substances, it may be used to identify an unknown material; or it may be employed to measure the concentration of a known substance in solution, providing the indices of refraction of solutions of known concentrations have been determined. These data are available in many handbooks.

There are several types of refractometers in industrial use. Several types hold a small sample of the solution between two

prisms positioned at the lower end of a telescope. Either the telescope or the prism block can be rotated to bring a sharp division of the field to coincide with cross-hairs in the eyepiece. The relative position of the two units gives a direct reading of refractive index.

The class represented by the dipping, or immersion type of refractometer is, in principle, much like the other instrument, but it has no auxiliary or lower prism. The main prism, at the lower end of a small telescope, is immersed directly in the liquid or solution to be examined. The reading is taken by means of a scale in the eyepiece of the telescope.

In all measurements of refractive indices, it is extremely important that the temperature of the solution and prisms be carefully controlled, since the variation of refractive index with temperature is of considerable magnitude.

Colorimetric Methods. The use of colorimetric methods in chemical analysis depends upon comparative observations of the color intensity developed in a system or upon the absolute measurements of the amount of light absorbed by a system.

Visual Methods. The older colorimetric methods of the chemists, involving the comparison of the color of a solution of unknown concentration and a "standard" solution of known concentration, are still in use. Many simple colorimeters can be devised, requiring only a pair of flat-bottomed tubes of the same diameter and a source of axial illumination. By altering the depth of solution in each tube, a color match can be obtained. The calculation of the unknown concentration is simply made by the application of laws relating to the change in depth of color with a change in concentration.

The pH of a solution can be determined colorimetrically by comparing the color of the solution, after adding a suitable indicator, with a series of color standards containing the same indicator.

Photoelectric Methods. The methods of visual comparison are influenced by inherent differences in the eyes of various observers. To avoid this, newer instruments employ a photocell for making the comparison.

Spectrophotometric Methods. The actual measurement of the

amount of light absorbed by a system is also possible. Chemical analysis by photometric methods is accomplished best by measurement of the amount of light absorbed from a narrow band of the spectrum at various selected wavelengths. The instrument used for this purpose is the spectrophotometer. The absorption is plotted against wave length, giving an irregular curve. These methods need not be limited to the visible spectrum. Special spectrophotometric methods are used for comparing the colors of opaque substances. They are also used for measurements of brightness and reflectivity.

Nephelometric Methods. Nephelometric methods are based upon the observation and measurement of light which is scattered axially in a glass tube containing a suspension of finely divided solids (a turbid liquid) when the tube is illuminated by a beam of light perpendicular to the axis of the tube. A standard and a sample tube are placed side by side in a uniform beam of light. The length of one column of liquid is fixed, while the length of the other is varied until the two fields are of equal brightness. Although visual observations are quite satisfactory, the photocell has here too improved the reproducibility of results.

Microscopic Methods. The use of the microscope has been extended tremendously in recent years to include the examination of a great number of industrial materials. Microscopic methods have solved problems of analysis which, on a macro scale, appeared to be insoluble. The very small quantities required in microscopic methods have permitted the study of materials not available in larger amounts, and in many cases have promoted an appreciable saving of time.

Optical Microscopy. The use of the optical microscope has been standard practice in biological, medical, and metallurgical work for more than a century. The adaptation of microscopic methods to chemical and physical problems is somewhat more recent. The resolving power of an optical compound microscope is about 2,000 Angstrom units ($1/125,000$ th inch).

The analyst can employ a simple type of microscope for examination and identification of fibers of vegetable and animal origin; counting of dust particles, molds and yeasts; and study and measurement of sizes of crystal grains, etc.

With the chemical microscope, which is usually fitted with several important accessories, microchemical reactions can be studied, qualitative analysis of minute amounts of materials can be carried out, and the optical properties of crystals can be determined.

The petrographic microscope, one form of the polarizing microscope, is a precision instrument for the examination of the optical properties of rocks and minerals. It is used also for precise determination of the optical crystallographic properties of many substances.

The ultramicroscope is a modified microscope which permits the observation of light reflected by colloidal particles when they are indirectly illuminated. It is possible to perceive light scattered by a single particle which is much too small to provide an image in even the most powerful microscope.

A significant advantage in the use of microscopic methods is the ease of making record photographs, both in black and white and in color.

Electron Microscopy. The invention of the electron microscope has extended greatly the range of magnifications obtainable. Magnifications of 20,000 to 40,000 times are possible with this instrument. Its resolving power is as high as 20 Angstrom units (one twelve-millionth inch) and it is thus about a hundred times as powerful as the compound microscope. Images from the electron microscope are obtained only as photographs. Enlargement of these gives still greater magnification.

Spectroscopic Methods. When an element is heated to a high temperature in a flame, is subjected to the action of a high potential spark, or serves as an electrode in a low-voltage, high-current arc, it emits light of various wave lengths, which are characteristic of that element. This light is refracted by either a prism or a grating into a band of colored lines called a spectrum.

There are several kinds of spectra. The emission spectrum, comprising a series of bright lines or bands of various wave lengths against a dark background, is obtained from a luminous source such as a flame, electric spark, or electric arc. An absorption spectrum is obtained by introducing some light-absorbing medium between a luminous source and the spectroscopy. The

medium absorbs light of characteristic wave lengths from the spectrum of the source. This kind of spectrum appears as a set of dark lines or bands against a bright background.

Spectrometry is the name given to the measurement of wave lengths of absorption and emission bands of a spectrum.

The Spectroscope. The ordinary spectroscope consists of a slit of adjustable width, a collimating lens which forms parallel rays from the light entering through the slit, a prism made of glass of high dispersion (or a diffraction grating), and a telescope for viewing the spectrum; all these components are supported on a suitable mount. When light from a heated substance passes into the slit, a spectrum is formed which can be examined by means of the telescope. The characteristic lines of the spectrum are compared with a scale and their wave lengths measured.

The Spectrograph. The spectroscope can be converted into a spectrograph by replacing the telescope with a suitable photographic camera.

The spectrograph is preferred to the spectroscope, since it provides a record in the form of photographic films, which can serve as a medium for making very accurate measurements of wave length. Photoelectric devices are incorporated in some recently developed instruments for measuring the density or relative blackness of a line, thereby permitting an estimation of the quantity of any element present in a sample under examination.

For measurements in the ultraviolet region, quartz lenses and prisms are used since ordinary glasses do not transmit the ultraviolet satisfactorily. Investigations in the infrared region require a prism made of artificial rock salt with aluminum- or gold-coated mirrors instead of the usual lenses. A thermopile in the instrument detects and measures the intensity of radiation.

The Mass Spectrometer. Mass spectrometry is a technique for the separation of gaseous ions of different masses by the application of electric and magnetic fields. When the molecules or atoms of a substance, existing as a gas at low pressures, are bombarded by electrons from a heated filament, positively and negatively charged ions are produced. These ions are made to move by applying an electric field. Positive ions form a beam, which, when subjected to the action of a magnetic field, is deflected into a "spec-

trum." For constant magnetic field strength, the deflection of an ion is a function of its mass. These beams will affect a photographic plate; the spectral lines appearing thereon permit measurement of the masses of ions present, and the degree of black-

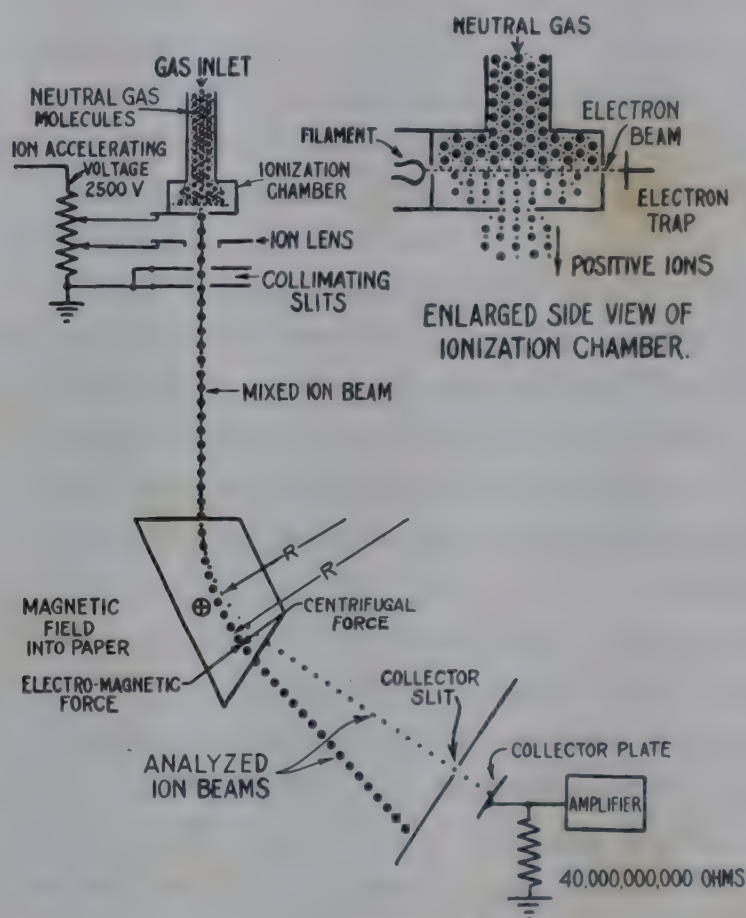


CHART 2

(General Electric Co.)

Figure 99. Mass Spectrometer (Elementary Diagram).

ening of the plate is a measure of the quantities present in the sample under study.

Other Physical Methods

Determination of Density. The determination of density, a relatively simple physical measurement, is of much importance to operational control. It is especially useful in routine plant control, since the purity or concentration of many substances can be expressed in terms of the density of solutions. The density of solids, such as minerals, salts and certain organic compounds, may be of great aid in identification.

Hydrometers constitute the simplest device for measuring liquid densities. They consist of a closed glass tube weighted at one end with mercury or lead shot, and enclosing a paper scale on which the density figures are printed. The hydrometer is immersed in the liquid and the density is read directly on the scale. There are several scales in common use.

The *pycnometer* is another laboratory device for measuring density. It is a tube, flask, or bottle, which can be filled to some index mark, and then weighed. Some pycnometers, such as the Sprengel type, are designed solely for liquids. The flask type can be used for measuring the density of both liquids and solids. The pycnometer permits very accurate density measurements.

The Westphal type *specific gravity balance* is a specially constructed balance on which the density of a liquid may be read directly from the position of riders on its beam. In effect, the balance determines the buoyant effect of a liquid upon a glass bob immersed in it. The use of certain accessories enables the density of solids to be measured.

The simplest method for measuring the density of gases is one in which a glass bulb of known volume is weighed before and after filling it with the gas. Temperature and barometric pressure must be noted as the measurement is made.

More precise determinations can be made with special types of the gas density balance.

Viscosity Measurements (Viscometry). Viscosity is the resistance offered by liquids to flow. Liquids can be roughly classified into two kinds, Newtonian and non-Newtonian. Newtonian liquids are those in which the volume flowing is directly proportional to the pressure applied; all others are non-Newtonian.

The measurement of viscosity is of great importance to the chemical engineer. Viscosity is an extremely important property of liquids in that it materially affects both their flow and the transfer of heat to and from them. In many cases of solid-liquid systems, viscosity is directly related to concentration of the solid in suspension and can be used as a measure of the concentration.

One common method for measuring viscosity involves the timed flow of a liquid through a capillary tube. Several laboratory instruments are based on this principle. In industrial practice,

especially in the petroleum industry, a capillary tube viscometer, known as the Saybolt, is used. In this instrument the oil being tested is allowed to flow from a cup through a capillary tube, and the time required to deliver a known volume of liquid is a measure of the viscosity.

The methods just described, when used with care, are satisfactory for determining the viscosity of Newtonian liquids. For non-Newtonian liquids, a different technique must be employed, since it is necessary to measure the viscosity as it changes with the rate of shear of the liquid. The rotational viscometer, sometimes called the concentric cylinder viscometer, has been developed for the study of both types. In this instrument a cylinder is caused to rotate at various known speeds in a cup containing the liquid under test. The viscous drag exerted by the liquid upon the cup is measured as a torque on the container. Other viscometers are also in use.

Thermal Measurements. The measurement of temperature as a process variable is a problem constantly confronting the chemical engineer. The measurement of temperature in the determination of melting and boiling points of materials is an extension of the same problem. The identification of unknown materials and determination of purity can be aided to a considerable degree if the melting and boiling points can be obtained and compared with values for known compounds.

The molecular weight of an unknown substance can be found if the depression of the freezing point and the elevation of the boiling point of a solution of the substance is measured.

The heating values of fuels and the heats of combustion of various substances depend upon the measurement of temperature rise when these materials are burned under controlled conditions. This technique is called calorimetry and the assembled instrument a *calorimeter*.

Surface Tension Methods. Surface tension is a force at the surface of a liquid which tends to produce a minimum surface area. The measurement of this property, important in the field of detergents, wetting agents, and flotation agents, is usually accomplished by determining the force necessary to pull a small wire ring away from a liquid surface in which it has been placed.

Distillation Methods. The distillation of liquid mixtures will often give valuable information relating to their composition. Some materials, such as gasoline and naphtha, are characterized by the percentage of a sample which distills over a specified range of temperature. A complete separation of mixtures by distillation can sometimes be effected, thus providing a method of determining purity.

Laboratory distillation approximates, in general, industrial distillation methods previously described. For laboratory research or for precise process control, the Podbielniak and other distilling apparatus permit very close separations.

25 : PACKAGING

The Packaging of Solids

The Packaging of Liquids

The Packaging of Gases

Packaging, a task which has often been dismissed by the chemical engineer as being one of small consequence, should never be considered lightly. Obviously, finished materials must be moved away from the plant in which they are produced and must be delivered to the consumer of these products in a form free from contamination and deterioration. Further, products must often be stored for some period of time either in the producer's plant, or in the consumers' warehouses. During this period they must be protected from both mechanical damage and chemical and biological spoilage.

Actually, plant production and operation are sometimes profoundly influenced by the type of package which may be available. Further, it is axiomatic that a product, to be marketed successfully, must be placed in attractive and sales-compelling containers. This is particularly true in the field of consumer products where the appearance of the package and the label are often important items in competitive sales.

The engineer should, therefore, know what types of containers are available, and be informed on the methods and machines which are employed to fill them. Packaging procedures extend from the old fashioned practice of hand packing, still widely used, to the modern use of completely automatic high-speed filling machinery.

Packaging is always a balance between low cost and light weight of the container on one hand, and permanence, rigidity, and complete protection of the packaged product on the other. The container which is selected represents a balance between these features.

The technical factors which should be considered when choosing a container and a technique for its filling are as follows:

1. State of the product (solid, liquid or gas)
2. State of sub-division
3. Vapor-pressure of material
4. Freezing point
5. Corrosive properties
6. Chemical stability
7. Physical stability
8. Rate of production
9. Cost and selling price
10. Trade requirements
11. Optimum size of package
12. Federal and state regulations.

THE PACKAGING OF SOLIDS

Solid substances, as finished products, may exist in various states of subdivision. Thus, sulfur may be sold as a solid filling in a tank or drum, shipped in sacks as lumps, or in sacks, paper cartons, or glass bottles as a finely-divided powder.

Bulk Packaging of Solids

Solids in bulk may be shipped in ocean or lake freighters, barges, freight cars and trucks. Thus, in a sense, these transportation devices are "containers." Consumers able to use full cars or shiploads of bulk material benefit substantially in the price of their materials through lower loading costs, by avoiding the cost of the smaller packages, and by easier unloading. Bulk loading of many materials, such as cement, once handled almost entirely in bags, has proven to be very successful and has lowered their delivered cost appreciably.

Further, bulk loading can save time and expense to the consumer by avoiding the introduction of contaminants such as fibers, strings, and other residues from the bags. This is particularly important to bakers, candy makers, and manufacturers of other food products.

Coal, coke, limestone, iron ore, grains, and many other

commodities are nearly always shipped in bulk. Cars used for shipping certain classes of bulk commodities must often be thoroughly cleaned to remove residues and trash from previous shipments, sometimes be refinished on the inside, relined with paper, or otherwise prepared to hold the new load of material. Leakage of granular or powdered solids from railroad cars is always a troublesome feature. To guard against such loss the car must be carefully inspected for leaks, and repaired if necessary.

The mechanical devices employed for bulk loading may be considered in the category of "packaging machinery." The simplest method for the loading of bulk commodities is to discharge them into a steamship or freight car by gravity through a chute or pipe leading from the warehouse storage bins. The belt and other continuous conveyors are very effective for the same task. Cranes of various kinds are also widely used for loading from piles of materials. Some materials, such as grains, or finely-powdered minerals, permit the use of pneumatic conveyors.

Packaging in Bags

Packaging of solids such as sugar, fertilizers, stock feed, many chemicals, grains, lime, and cement, in bags is a widespread practice of long standing. Packaging in containers small enough to be lifted by one man is almost a necessity for material destined to be used in retail trade.

Burlap, jute, and cotton bags have been used for many years. More recently paper is replacing cotton and burlap for bag construction. The lower initial cost of paper bags and their easy availability and improved quality have led to this change. Also, the generally unsatisfactory requirement of having to use returned cloth bags is avoided by this change.

To effect a saving of labor in filling bags, considerable effort has been spent on the design and manufacture of special packing machinery. These machines receive material from a storage bin, weigh it automatically and then discharge it into the bag. They may also be arranged to interrupt filling operations when the bag, held on a scale platform, reaches the proper weight. A minimum of hand operations is required; these include placing the bag in position in the machine, and in the case of cloth

bags, directing the top of the bag through the head of a sewing machine. Many food products are packaged in small paper bags of 1, 5 or 10 lb. sizes by a machine which is completely self-contained. Paper bags, as well as cloth ones, are often pre-closed while empty, and are filled through patented flap closures in the bottom.

When filling loose powders or granular solids into any container, the use of a vibrating platform designed to shake the container vigorously increases the amount of material which can be packed, or conversely, effects a reduction in container size for a given weight of solid.

Packaging in Boxes

Many chemicals were formerly packed in wooden boxes; today wooden boxes are used only for packaging fragile materials which require the utmost protection from mechanical damage.

Wooden boxes for other uses have been largely supplanted by boxes made of plain or corrugated paper board. Although not as rigid as the wooden box, the paper box is superior to it in many respects. It is trim in appearance, easy to pack, close, and mark, and equally easy to open. Further, it is substantially cheaper in first cost, and since it is much lighter in weight, reduces shipping costs.

The smaller sizes of paper boxes are used to package many different solid products. Paper boxes and cartons are made in



(B. F. Gump Co.)

Figure 100. Automatic Net Weigher. Gravity feed (Section view).

a wide variety of shapes and sizes. They may be plain paper board or paper coated or impregnated with waxes, plastics or paints. Laminating the board to give excellent strength, proper bulk and stiffness, and to produce a waterproof container is also common practice.

Completely automatic machines are available which will open the boxes, fill, settle, seal and label them.

Packaging in Drums and Barrels

Wooden barrels were once widely used as containers for solid materials. The high cost of cooperage has stimulated the development of cheaper forms of cylindrical containers. Drums made of metal or fiber have almost entirely replaced the wooden barrel for this service.

Packaging in Metal or Paper Cans

Metal cans holding from one to a hundred pounds of solid have long been used as packages for solid material. The smaller size cans are of particular interest when use requirements are small and particularly when this feature is combined with a rapid deterioration of the contents after they have been exposed to air. Metal cans are closed by either crimped or pressed-on lids, or where spoilage by air is certain, the closure may be sealed in place by a low melting solder.

Paper is invading this field as it has that of wooden boxes and metal or wooden barrels. The ability of paper-makers to make a container which is rigid, waterproof, reasonably permanent and low in cost has made paper cans popular for many uses once reserved solely for metal or wood.

Packaging in Glass

Virtually every kind of powdered, flake, or crystalline solid is packaged in glass bottles. They range in size from tiny vials to glass jars holding up to 10 or more lbs. The screw-cap, of metal or plastic, is now in almost universal use for closure. The use of glass for packing solids is also losing favor to the use of paper. Glass does, however, have greater permanence, has better appearance, and generally gives better protection than

paper, but has these advantages only at higher cost and considerably greater shipping weight.

Seal Coating

The procedure introduced during the last war of using an impervious coating of waxes or strippable plastic to enclose and seal many products has been used only to a limited extent in the chemical industry. Many containers of chemicals are sealed to prevent the entrance of moisture and the loss of volatile substances through the closure. Sealing also assures the customer that no tampering with the container has occurred before its receipt. There are undoubtedly many fields of application of these seal-coating materials which are as yet undeveloped.

Use of Desiccants in Packaging

The practice of placing bags of desiccants in boxes containing mechanical equipment can be extended to the packaging of many solid substances which require complete freedom from moisture.

PACKAGING OF LIQUIDS

The vapor pressure of a liquid to be packaged and shipped is the guide to the type of container required for the purpose. Low-pressure containers are suitable for most liquids, but liquids of high volatility must be placed in high-pressure vessels. Corrosion resistance, and therefore, the material of construction of the container is of far greater importance in packaging liquids than it is in packing solids.

Bulk Packaging of Liquids

Liquids which are handled in large enough quantities may be shipped in tankers, barges, or railroad tank-cars. Rail transportation of liquids is supplemented by the use of tank trucks. Thus, as in the case of shipping solids in bulk, the transportation units for handling liquids, such as tanker and tank cars can be considered as containers. Unless the equipment is always

used in one commodity service, it is necessary to clean the tanks, often at considerable cost, before they can be used for other products.

Packaging Liquids in Drums and Barrels

Wooden barrels, formerly much used, are still employed as containers for alcoholic beverages, vinegar, and various other liquids. Excellent corrosion resistance, and freedom from contamination from corrosion products is the outstanding feature of wooden barrels. For handling liquids which keep the wood wet and tight, the wooden barrel is quite satisfactory. Wood is, however, easily contaminated by foreign substances, and this, together with the increasing cost of cooperage, is discouraging any expanding use of the wooden barrel as a package for liquids.

Drums made of various metals and alloys are now in wide use, supplanting wooden barrels to a very large extent. These containers are made in a number of styles to make them easy to handle, store, empty or clean. Metal drums vary in size from about 5 gallons to 55 gallons.

A recent development is a collapsible rubber fabric drum. This drum is convenient to fill and empty, and the fact that it can be collapsed into a space a fraction of its actual volume makes it possible for it to be returned to the shipper at a cost well under that of the cost of shipping a standard metal container.

Packaging Liquids in Bottles

Glass containers for liquids range in size from tiny ampoules to carboys of about 12-gallons capacity. Carboys are employed for shipping many chemicals such as acids and ammonia when intermediate quantities are required. Carboys are crated in wooden boxes for protection and to provide an easy way of handling them.

Smaller glass containers are closed with ground glass stoppers, plastic or metal screw-caps, or corks or rubber stoppers. The ampoule, which is a small glass vial, is ordinarily closed by fusing its neck in a flame. As in the case of packaging solids, liquids are measured and the bottles are filled and labeled by

automatic machinery. A fairly recent innovation in the design of bottles has been the introduction of easy pouring and dripless necks.

Within recent years small bottles made of polythene, a somewhat pliable synthetic resin, have become available. This material will withstand the corrosive action of many chemicals. Plastic containers are often used to package cosmetic preparations and their use for other consumer items will undoubtedly expand. The nonbreakable feature of the plastic container, its lighter weight, and the better grip which can be obtained on its surface, all contribute to its use. The fact that the bottle can be distorted somewhat to make it easy to pack, and can be squeezed to deliver a few drops of its contents at a time are features which make it unique as a container.

Packaging Liquids in Metal Cans

Foodstuffs in billions of pounds, paints and varnish and lubricating oils in millions of gallons, and a host of other products are packaged in metal cans. Modern practice is to weigh the product into the can, and then to seal, label, and check weigh the can by completely self-contained automatic machinery.

Packaging in Tubes

Compressible metal tubes, long a favorite method for packaging pastes and creams for medicinal or domestic use, are suitable for a number of commercial items. Tubes are easily filled, and their ability to protect the contents from exposure to the air, even as material is being removed from them, are both features of importance.

PACKAGING OF GASES

In general, it is impractical to package and ship gases at low pressures; therefore, most gases, such as nitrogen, oxygen, and hydrogen are compressed and stored and shipped in high-pressure steel cylinders.

Chlorine and other gases which are easily liquefied are bottled in steel cylinders or tanks. Several gases, notably acety-

lene, can, at slightly increased pressures, be dissolved in liquids or absorbed by solids in large amounts, and will be released when the pressure is reduced.

Tank cars of the easily liquefiable gases are also filled as a shipping container. A modern development in this field is the insulated tank car designed to hold several thousand gallons of liquefied oxygen, nitrogen, or other so-called "fixed" gas. Metal Dewar flasks holding from 5 to 20 liters of liquefied gas are common shipping containers. Since gas is slowly released from these containers, their use is limited to gases which are non-toxic and nonflammable.



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